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ANALYSIS OF OXYGEN USE UNDER RIVER ICE

by



DONALD PETER CORRIGAN

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

DEPARTMENT OF CIVIL ENGINEERING

EDMONTON, ALBERTA

FALL, 1970

Thesis
1970 F
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THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read,
and recommend to the Faculty of Graduate Studies for
acceptance, a thesis entitled ANALYSIS OF OXYGEN USE
UNDER RIVER ICE, submitted by DONALD PETER CORRIGAN in
partial fulfilment of the requirements for the degree
of MASTER OF SCIENCE.

Date: June 10,

ABSTRACT

ANALYSIS OF OXYGEN USE UNDER RIVER ICE

The object of this study was to assess a few of the many parameters associated with the waste assimilation capacity of the North Saskatchewan River under conditions of ice-cover. Results of a field investigation into the rates of deoxygenation (K_d) and BOD-5-20 removal (K_r) in the river, as well as a formula to predict DO utilized downstream from Edmonton are presented. The study area included the reach of river from Edmonton to Battleford, Saskatchewan.

During the field study which extended from January to March, 1970, four time-of-travel, as well as four separate DO-BOD sampling runs were undertaken.

Rhodamine B and Fluorescein dye solutions were utilized as soluble tracers in the time-of-travel measurement studies. Based on the results from these dye tracing tests, a velocity-discharge relationship under ice-cover conditions was developed. Mean river velocities varied from 1.19 to 1.34 fps for discharges of 2390 and 2930 cfs respectively.

The study showed that reaeration takes place in the open water reach, which extended up to 18 miles downstream from Edmonton. The rate of reaeration (K_2) was estimated to be 0.20 per day (base 10 log). Deoxygenation commenced approximately 30 miles downstream from Edmonton. The rate of deoxygenation (K_d), which appeared to vary with discharge and location along the river, was found to vary from 0.165 to 0.013 per day (base 10).

An equation was developed to indicate the dissolved oxygen usage relative to any given location downstream from Edmonton. This equation is of the general form, $D_2 = D_1 + S \log \frac{t_2}{t_1}$, where D_2 and D_1 represent the dissolved oxygen utilized in the river t_2 and t_1 days respectively downstream from Edmonton. The use of the developed equation is limited to river discharges and BOD loadings similar to those found in this study.

Due to variable BOD results, a rate describing BOD removal throughout the entire study area could not be established. BOD removal rates (K_r) for various short reaches of river varied from 0.10 to 0.49 per day (base 10). No definite relationship between BOD reduction and DO utilization could be established.

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GLOSSARY OF TERMS

Assimilation	The absorption and utilization of a nutrient by an organism.
Biochemical Oxygen Demand	The amount of oxygen required for the biological oxidation of the organic matter in a liquid.
Biological Oxidation	A biochemical reaction in which materials combine with oxygen to produce energy.
Dissolved Oxygen Deficit	The difference between the actual and the saturation value of dissolved oxygen.
Dissolved Oxygen Utilization	The total amount of dissolved oxygen used to satisfy the oxygen demand of organic matter within a given reach of river.
Longitudinal Dispersion	The longitudinal mixing or spreading of a concentrated mass of pollutant or tracer in a natural stream.
Saturation	State of maximum solubility of atmospheric oxygen in a stream. The solubility varies directly with the atmospheric pressure at any given temperature.
Volatilization	The removal of certain organic compounds from a stream in the form of gaseous end products.

GLOSSARY OF SYMBOLS

D	Dissolved oxygen utilized (mg/ℓ)
DO	Dissolved oxygen concentration (mg/ℓ)
D_L	Diffusibility of oxygen (ft ² /hr)
H	Depth of flow (ft)
K	Rate constant (per day)
K_1	BOD reaction rate coefficient (per day)
K_2	Reaeration rate coefficient (per day)
K_3	Rate coefficient for removal of BOD by sedimentation and/or adsorption (per day)
K_d	Deoxygenation rate coefficient (per day)
K_r	Rate coefficient for total BOD removal in a stream (per day)
L	Ultimate 1st stage BOD
S	Slope coefficient of DO utilization (mg/ℓ)
t	Travel time (days)
T	Temperature (degrees celsius)
U	Velocity of flow (fps)

CHAPTER I

INTRODUCTION

1. Waste Oxidation in Streams

The natural ability of rivers to assimilate and stabilize organic wastes is limited. Organic wastes, when discharged into streams, create biological activity which exerts a demand on the dissolved oxygen resources of the stream. The normal sources of oxygen in the river are from the atmosphere, photosynthetic activity and that already present in the water.

Ice-cover conditions, such as that experienced on the North Saskatchewan River, effectively eliminate the oxygen supplied through normal surface reaeration and photosynthetic activity. Therefore, the permissible loading to natural waters, under ice-cover conditions, is governed by the amount of oxygen already present in the stream. This oxygen must be able to meet the biochemical oxygen demand (BOD) of the organic wastes, as well as to meet the requirements of growth and reproduction of the normal population of fish and other aquatic organisms.

The North Saskatchewan River, like many other rivers in the northern latitudes, may be covered with the

for periods as long as six months. These ice conditions, together with the inherent low water temperatures and low winter flows, substantially reduce the capacity of the river to effectively assimilate organic wastes. This study is focused on a few of the many physical, chemical and biological factors associated with self-purification of rivers under ice-cover conditions.

2. Past Problems

During the early 1950's, when the Alberta Department of Health began chemical and bacteriological examination of the river during the winter months, very low dissolved oxygen (DO) levels were found downstream from Edmonton. At Lloydminster Ferry the DO often fell below 1 mg/l for several weeks (Paterson, 1966).

During the winter of 1955-56, the DO level 100 miles downstream from Edmonton was zero. This led to the introduction, by the Alberta Division of Environmental Health Services, of stringent control of all wastes discharged to the river. During the 1960's, due to the pollution abatement program and increased winter flows, DO levels at Lloydminster Ferry have been maintained between 4-6 mg/l (Alberta Division Environmental Health Services).

3. Present Problems and Study Objectives

Most research and literature relating to the natural self-purification ability of streams has been centered on rivers flowing under warm, summer conditions. Very little investigation and study has been directed towards rivers flowing at low temperatures ($0-5^{\circ}\text{C}$) and under ice-cover conditions.

This study is part of a continuing program, being undertaken by the Department of Civil Engineering, University of Alberta, investigating problems of pollution and bio-oxidation in ice-covered rivers. Briggs (1966) carried out laboratory studies of oxidation rates at temperatures at or close to zero degrees centigrade. Cameron (1967) studied river characteristics such as sludge and slime deposits and attempted to formulate dissolved oxygen utilization downstream from Edmonton.

The goal of this study is: (1) to determine reasonable mean velocities for various discharges under ice-cover by time-of-travel studies, (2) to verify and enhance Cameron's formulation of dissolved oxygen levels downstream from Edmonton, and (3) to attempt an estimate of the river BOD removal rate constant (K_r) and the deoxygenation rate constant (K_d). Since some BOD is removed by other than direct oxidation, these constants may not have the same value, even under ice-cover.

4. Study Limitations

An extensive study of the biological, chemical and physical forces of purification of rivers flowing under ice-cover conditions would involve workers from several disciplines and many years of effort. The many and varied parameters could each provide a separate area for study and research. In the short period of 4-5 months, when the ice conditions are favourable for field investigation, it is necessary to limit the scope of investigation.

As experienced by Cameron (1967), a major portion of the field time available was expended on the time-of-travel studies. Due to higher than normal winter temperatures during the months of November and December, favourable ice conditions for this study were confined to the first three months of 1970. This required some overlapping of time-of-travel studies and BOD-DO sampling runs. Because of the shorter period of favourable ice conditions, the number of sampling runs was reduced from the originally planned eight to four runs.

Despite the shorter field investigation period, it is felt that the data obtained was sufficient to establish most of the study's objectives.

CHAPTER II

DESCRIPTION OF THE STUDY AREA

1. General Description

The North Saskatchewan rises in the Rocky Mountains, some 180 miles southwest of Edmonton (FIGURE 1). Supplied by melting snows and glaciers, the river flows northeast across Alberta into Saskatchewan where it joins the South Saskatchewan River east of Prince Albert. The river then flows as the Saskatchewan River into Lake Winnipeg, which drains into the Hudson Bay via the Nelson River (FIGURE 2).

The river rises some 5,000 feet above sea level and flows approximately 330 miles to Edmonton, where the reference low stage water surface elevation is 2010.6 feet above sea level (FIGURE 3). In the study area, from Edmonton to Battleford, Saskatchewan, the river flows through rolling parkland, dropping some 490 feet in a distance of 328 miles (FIGURE 3). The river valley is characterized by steep valley banks and gravel flood plain. The river bed in the main channel, which is bound by tree and shrub roots, is mostly gravel with the side banks of the incised channel of a finer cohesive material. Trees on the flood plain are mainly spruce and poplar (Blench, 1969).



FIGURE 1

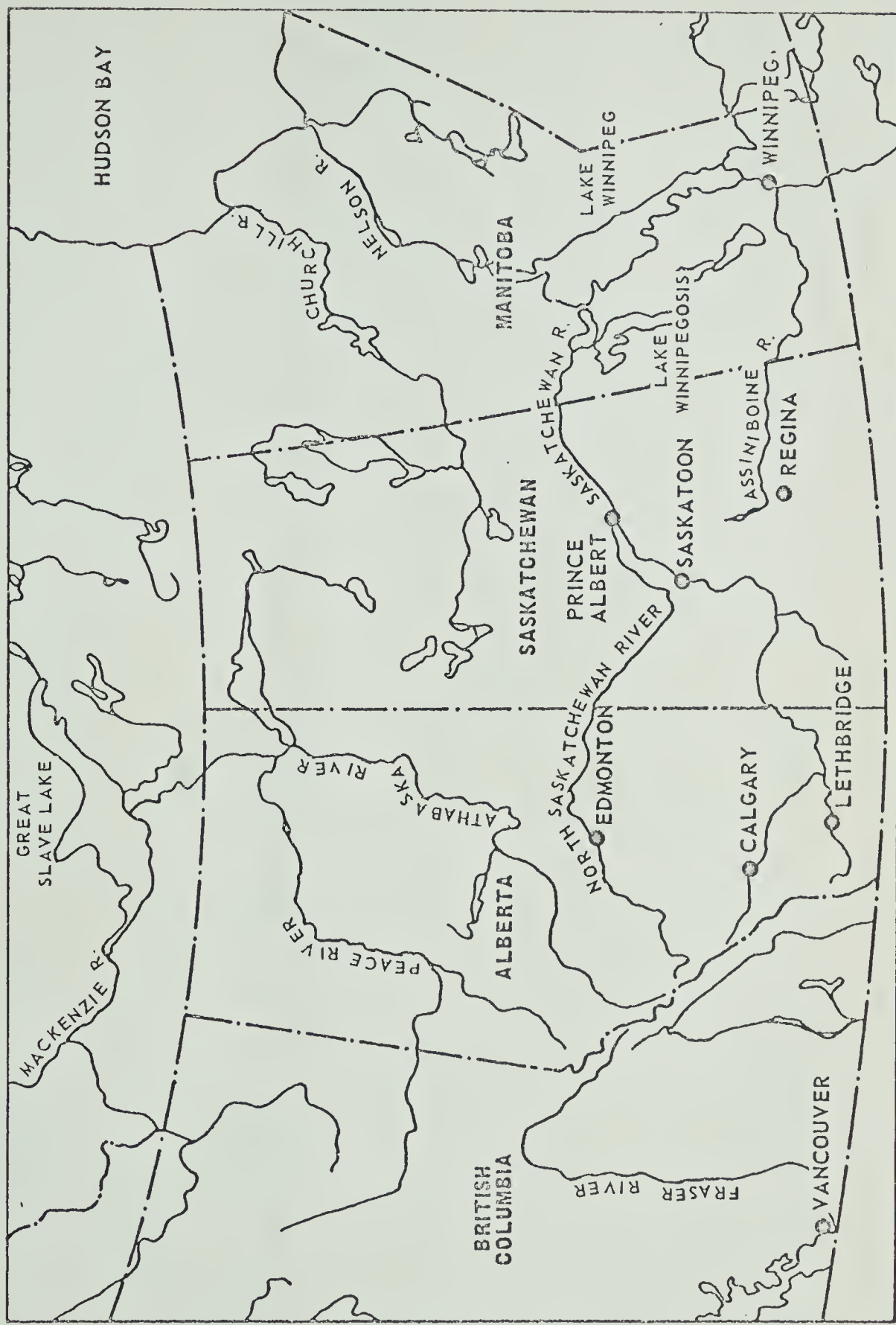
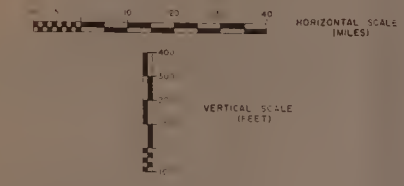


FIGURE 2: SASKATCHEWAN RIVER SYSTEM IN WESTERN CANADA

LONGITUDINAL PROFILE OF THE NORTH SASKATCHEWAN RIVER IN ALBERTA



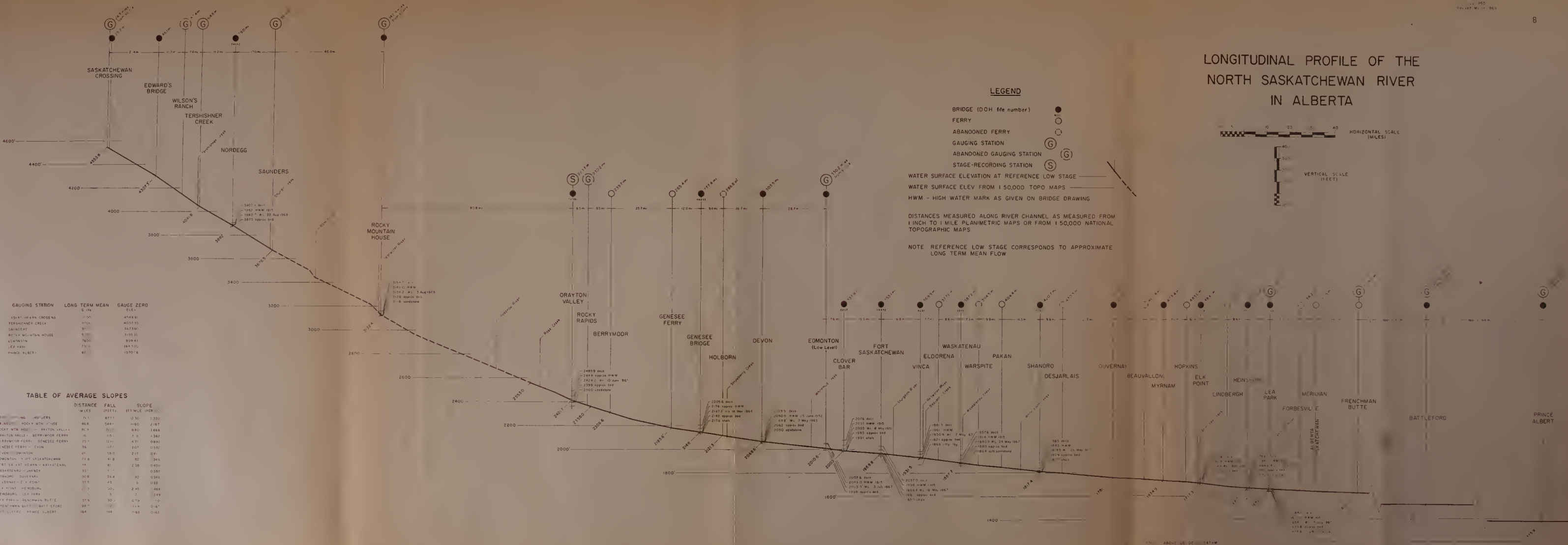
LEGEND

- BRIDGE (DOH file number)
- FERRY
- ABANDONED FERRY
- GAUGING STATION
- ABANDONED GAUGING STATION
- STAGE-RECORDING STATION

WATER SURFACE ELEVATION AT REFERENCE LOW STAGE
WATER SURFACE ELEV FROM 1:50,000 TOPO MAPS
HWM - HIGH WATER MARK AS GIVEN ON BRIDGE DRAWING

DISTANCES MEASURED ALONG RIVER CHANNEL AS MEASURED FROM
1 INCH TO 1 MILE PLANIMETRIC MAPS OR FROM 1:50,000 NATIONAL
TOPOGRAPHIC MAPS

NOTE REFERENCE LOW STAGE CORRESPONDS TO APPROXIMATE
LONG TERM MEAN FLOW



GAUGING STATION	LONG TERM MEAN	GAUGE ZERO
	G. 176	ELEV.
EDMONTON CROSSING	1701	4748.81
TERSHISHNER CREEK	1704	4657.53
SAUNDERS	50	3673.61
ROCKY MOUNTAIN HOUSE	5	3125.31
EDMONTON	7600	3094.41
LEA PARK	7700	2874.00
PRINCE ALBERT	87	1970.18

TABLE OF AVERAGE SLOPES

DISTANCE	FALL	SLOPE
MILES	FEET	FT/MILE (PER MIL)
1000	100	0.10
2000	200	0.10
3000	300	0.10
4000	400	0.10
5000	500	0.10
6000	600	0.10
7000	700	0.10
8000	800	0.10
9000	900	0.10
10000	1000	0.10
11000	1100	0.10
12000	1200	0.10
13000	1300	0.10
14000	1400	0.10
15000	1500	0.10
16000	1600	0.10
17000	1700	0.10
18000	1800	0.10
19000	1900	0.10
20000	2000	0.10
21000	2100	0.10
22000	2200	0.10
23000	2300	0.10
24000	2400	0.10
25000	2500	0.10
26000	2600	0.10
27000	2700	0.10
28000	2800	0.10
29000	2900	0.10
30000	3000	0.10
31000	3100	0.10
32000	3200	0.10
33000	3300	0.10
34000	3400	0.10
35000	3500	0.10
36000	3600	0.10
37000	3700	0.10
38000	3800	0.10
39000	3900	0.10
40000	4000	0.10
41000	4100	0.10
42000	4200	0.10
43000	4300	0.10
44000	4400	0.10
45000	4500	0.10
46000	4600	0.10
47000	4700	0.10
48000	4800	0.10
49000	4900	0.10
50000	5000	0.10
51000	5100	0.10
52000	5200	0.10
53000	5300	0.10
54000	5400	0.10
55000	5500	0.10
56000	5600	0.10
57000	5700	0.10
58000	5800	0.10
59000	5900	0.10
60000	6000	0.10
61000	6100	0.10
62000	6200	0.10
63000	6300	0.10
64000	6400	0.10
65000	6500	0.10
66000	6600	0.10
67000	6700	0.10
68000	6800	0.10
69000	6900	0.10
70000	7000	0.10
71000	7100	0.10
72000	7200	0.10
73000	7300	0.10
74000	7400	0.10
75000	7500	0.10
76000	7600	0.10
77000	7700	0.10
78000	7800	0.10
79000	7900	0.10
80000	8000	0.10
81000	8100	0.10
82000	8200	0.10
83000	8300	0.10
84000	8400	0.10
85000	8500	0.10
86000	8600	0.10
87000	8700	0.10
88000	8800	0.10
89000	8900	0.10
90000	9000	0.10
91000	9100	0.10
92000	9200	0.10
93000	9300	0.10
94000	9400	0.10
95000	9500	0.10
96000	9600	0.10
97000	9700	0.10
98000	9800	0.10
99000	9900	0.10
100000	10000	0.10

FIGURE 3

2. Climate

The climate in the vicinity of Edmonton is described as a cold, temperate climate. Located in a protective position in the lee of the Rocky Mountains, Edmonton receives an annual average precipitation of 18.5 inches, of which 65 per cent falls during the growing season of spring and summer.

The average winter temperature is 13.6°F from December to March inclusive. Low temperatures of -30°F , which occur on the average of three to four times each winter, remain for periods of up to several days. Depth of snow on the ground averages 7 inches by midwinter and seldom exceeds 14 inches in the city area.

A list of monthly and annual averages and extremes of records for the Edmonton area is shown in TABLE I.

3. River Discharge

The North Saskatchewan River is characterized by a large variation in the annual maximum and minimum mean daily discharge (FIGURE 4). The annual maximum daily discharges generally occur during a spring flood in April or May, and during a June or July summer flood. The spring floods are due to snowmelt and rainfall, while summer floods are caused by heavy rainfall, and snowmelt in the mountains. Inspection of the long term meteorological records for

TABLE I

METEOROLOGICAL SUMMARY FOR EDMONTON, ALBERTA*

Maximum Recorded Temperature - June, 1937	99°F
Minimum Recorded Temperature - January, 1886	-57°F
- February, 1893	
Mean Monthly Temperatures in °F	
January	6.6
February	11.2
March	22.1
April	39.5
May	52.1
June	57.8
July	63.1
August	60.0
September	51.5
October	41.2
November	24.5
December	13.3
Mean Annual Monthly Temperature	36.9°F
Mean Annual Rainfall	13.26 inches
Mean Annual Snowfall	58.8 inches
Mean Total Annual Precipitation	18.6 inches

*Data from 1969 Annual Meteorological Summary for Edmonton,
 Meteorological Branch, Federal Department of Transport.

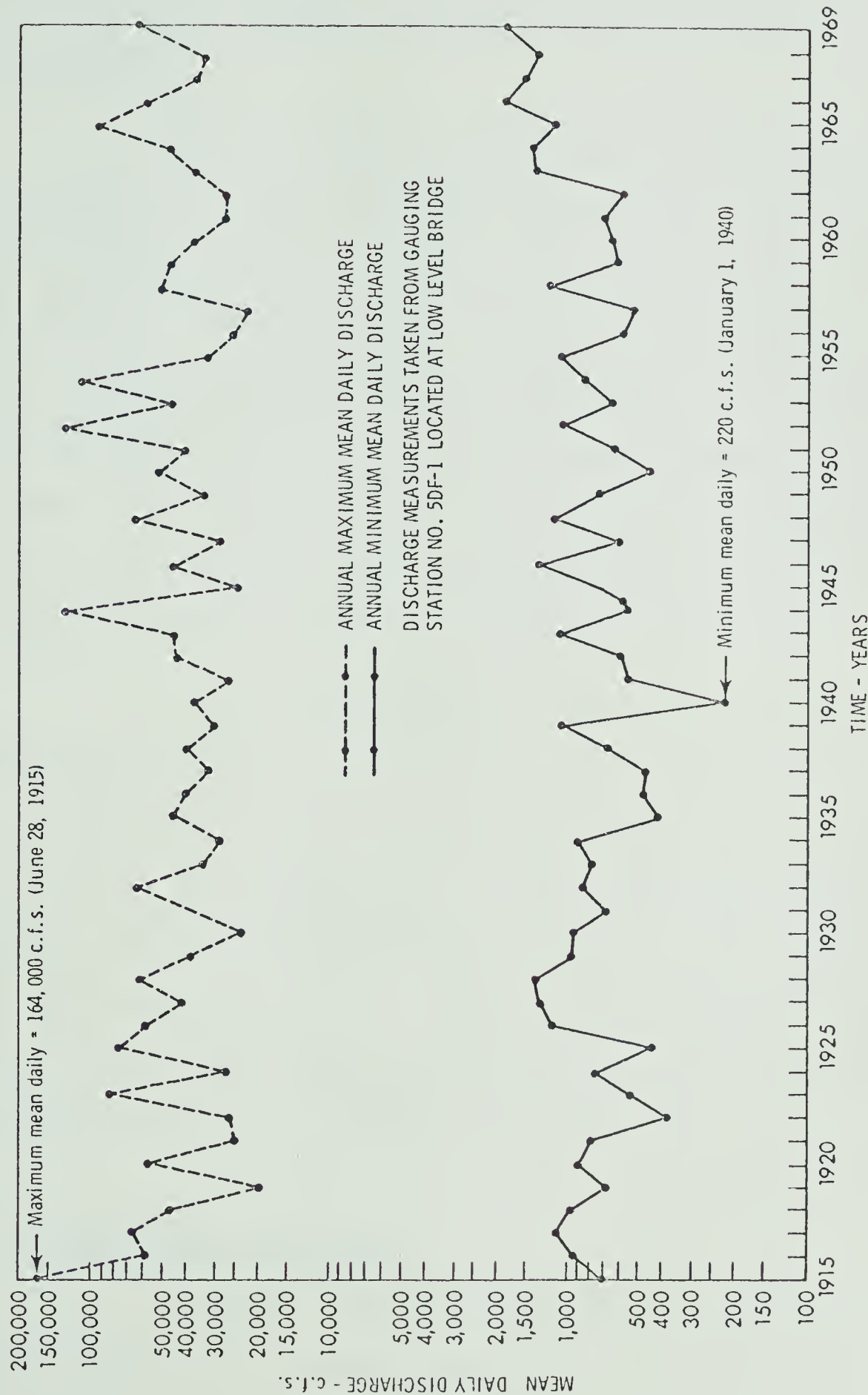


FIGURE 4: ANNUAL MAXIMUM AND MINIMUM MEAN DAILY DISCHARGES IN NORTH SASKATCHEWAN RIVER AT EDMONTON - 1915 to 1969

Edmonton shows that nearly 51 per cent of the mean annual precipitation occurs during the months of April to July inclusive.

Prior to the construction of the Brazeau Dam (FIGURE 1) in 1961, the North Saskatchewan River at Edmonton, generally experienced winter flows of less than 1000 cfs (FIGURE 4). This dam was constructed to provide storage for winter release and power development and to reduce flood peaks reaching the North Saskatchewan from the Brazeau River. It is expected that with full utilization of the dam, winter minimum mean daily flows in the North Saskatchewan through Edmonton should not drop below 2000 cfs.

A plot showing the average daily discharge at Edmonton during the 1969-70 winter month period is shown in FIGURE 5. Of particular interest is the steadying influence of the Brazeau Dam on the discharge through Edmonton during the months of January to March, which was the period of field investigation. During this three month period, the maximum mean daily discharge was 3340 cfs while the minimum mean daily discharge was 2050 cfs.

4. Ice-Cover Conditions

The North Saskatchewan River is generally covered with ice from 5-6 months per year. Ice conditions normally appear in the latter part of October or early November, and usually remain until the middle of April. During the

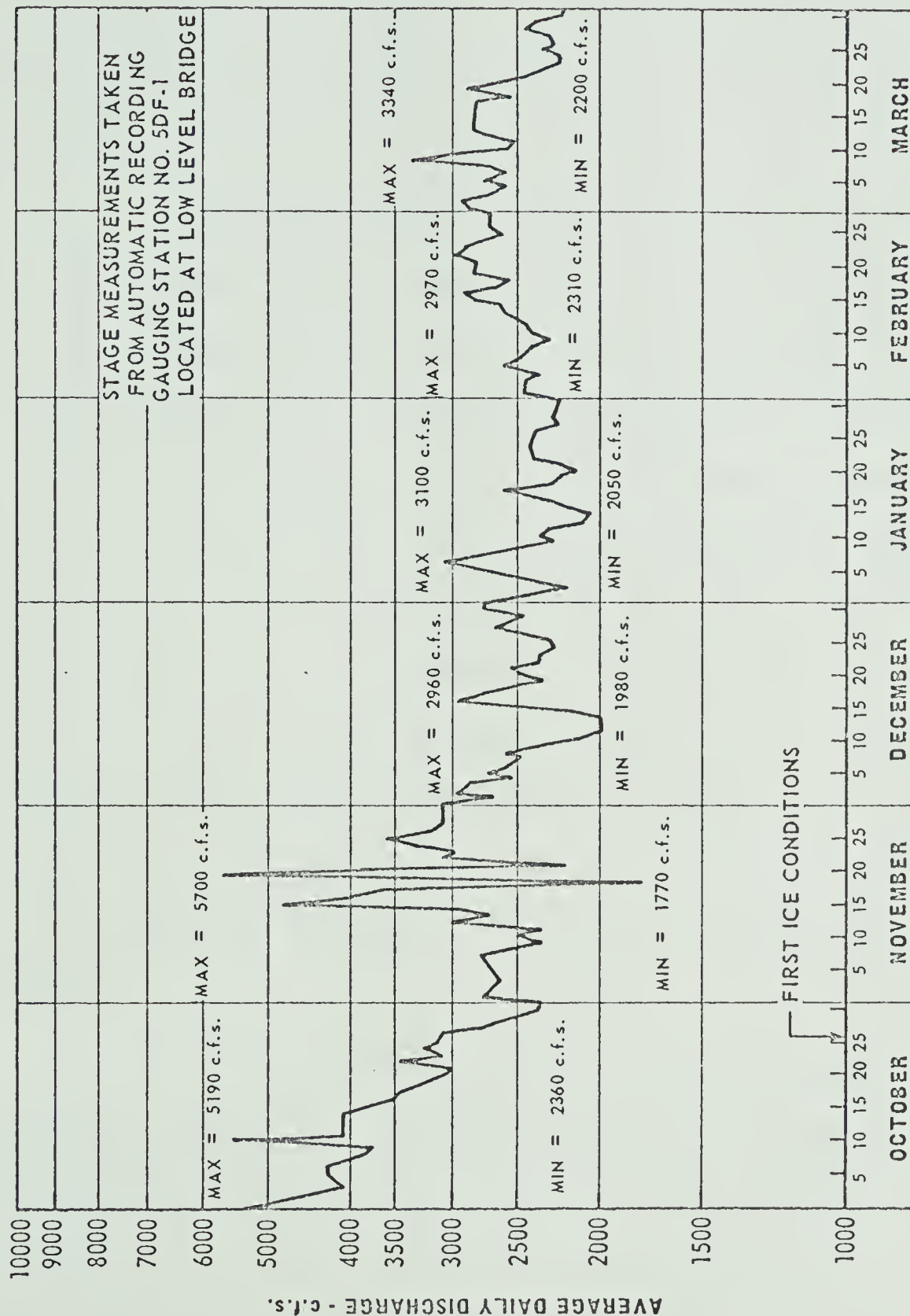


FIGURE 5: MEAN DAILY DISCHARGE IN NORTH SASKATCHEWAN RIVER AT EDMONTON DURING 1969 - 70 WINTER PERIOD.

1969-70 winter period, first ice conditions appeared on October 26 and last ice conditions occurred on April 13th. Cameron (1967) determined the frequency distribution of the lengths of ice cover periods for the period from 1915 to 1965 and this is shown in FIGURE 6.

Of particular interest to this study was the above normal monthly temperatures during the months of November and December, 1969. During November, 21 days of temperatures above freezing substantially restricted ice build-up and caused several high discharge peaks (FIGURE 5). During December there were 11 days in which temperatures were above freezing and only one day when temperatures were below zero. The mean daily temperature of December was 21.7°F , 7.8 degrees above normal. These higher temperatures effectively prevented ice build-up to a thickness favourable for field investigations and restricted the time available for field study to the months of January to March.

In the Edmonton area, cooling, domestic and industrial waste-water effluents keep the river ice-free downstream from the 105th Street Bridge (FIGURE 7). The length of river that remains open is dependent upon the air and waste water temperatures. The open water stretch is characterized by narrow shelves of ice (25 to 50 feet wide) along the banks, gradually increasing until the

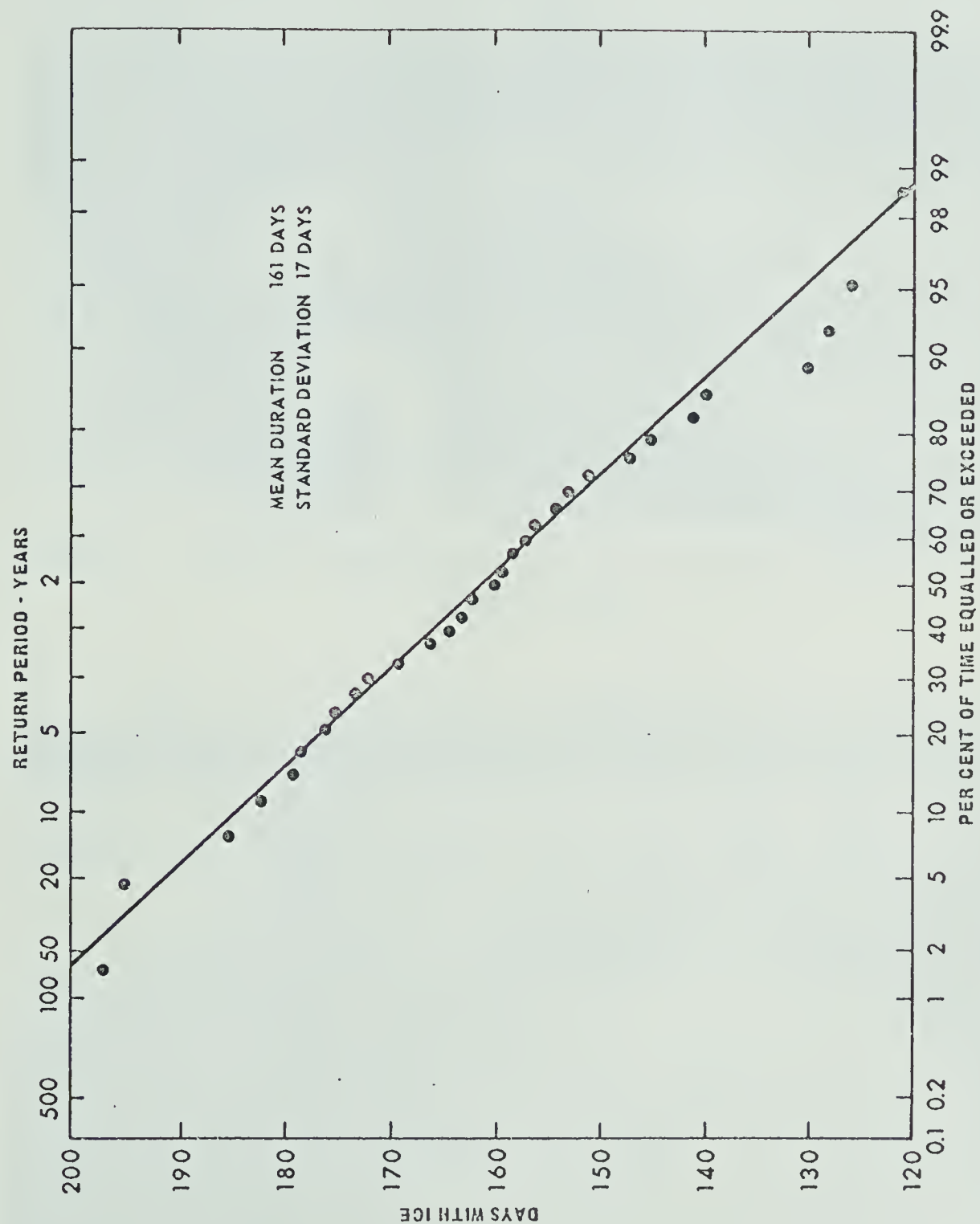


FIGURE 6: DURATION OF ICE - NORTH SASKATCHEWAN RIVER 1915 - 1965
(from Cameron 1967)

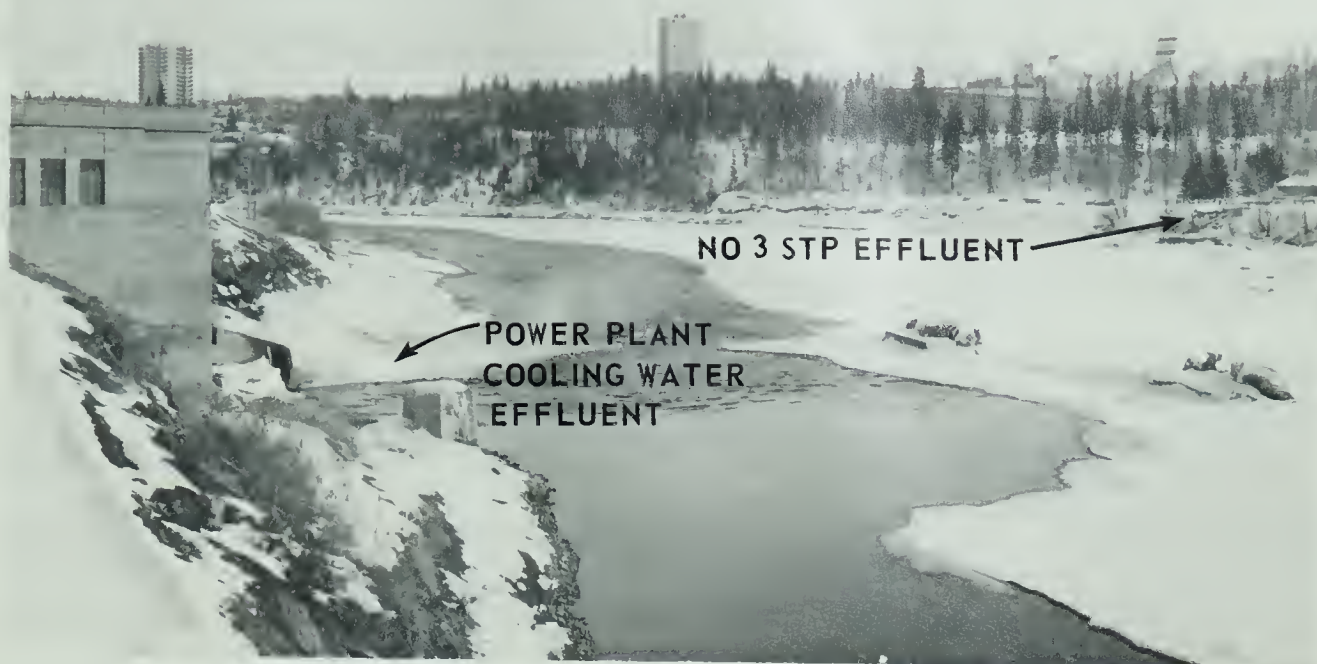


FIGURE 7: NORTH SASKATCHEWAN RIVER AT CITY OF EDMONTON POWER PLANT



FIGURE 8: NORTH SASKATCHEWAN RIVER AT CLOVER BAR BRIDGE
JANUARY 1970

channel is completely covered, normally 1-2 miles downstream from the Clover Bar Bridge (FIGURE 8). This was found to be the case during the month of January when colder weather prevailed and the mean monthly temperature was 2.7⁰ F. However, during the last 3 days of January, maximum daily temperatures above freezing caused the open stretch of river to extend past the City of Edmonton sewage lagoons (FIGURE 9). Above normal temperatures during February and March maintained the open water stretch past the sewage lagoons 16.5 miles downstream from the 105th Street Bridge. During the month of March, the main channel ice thickness at the Fort Saskatchewan Bridge (25 miles downstream from the 105th Street Bridge) was only 3 inches.

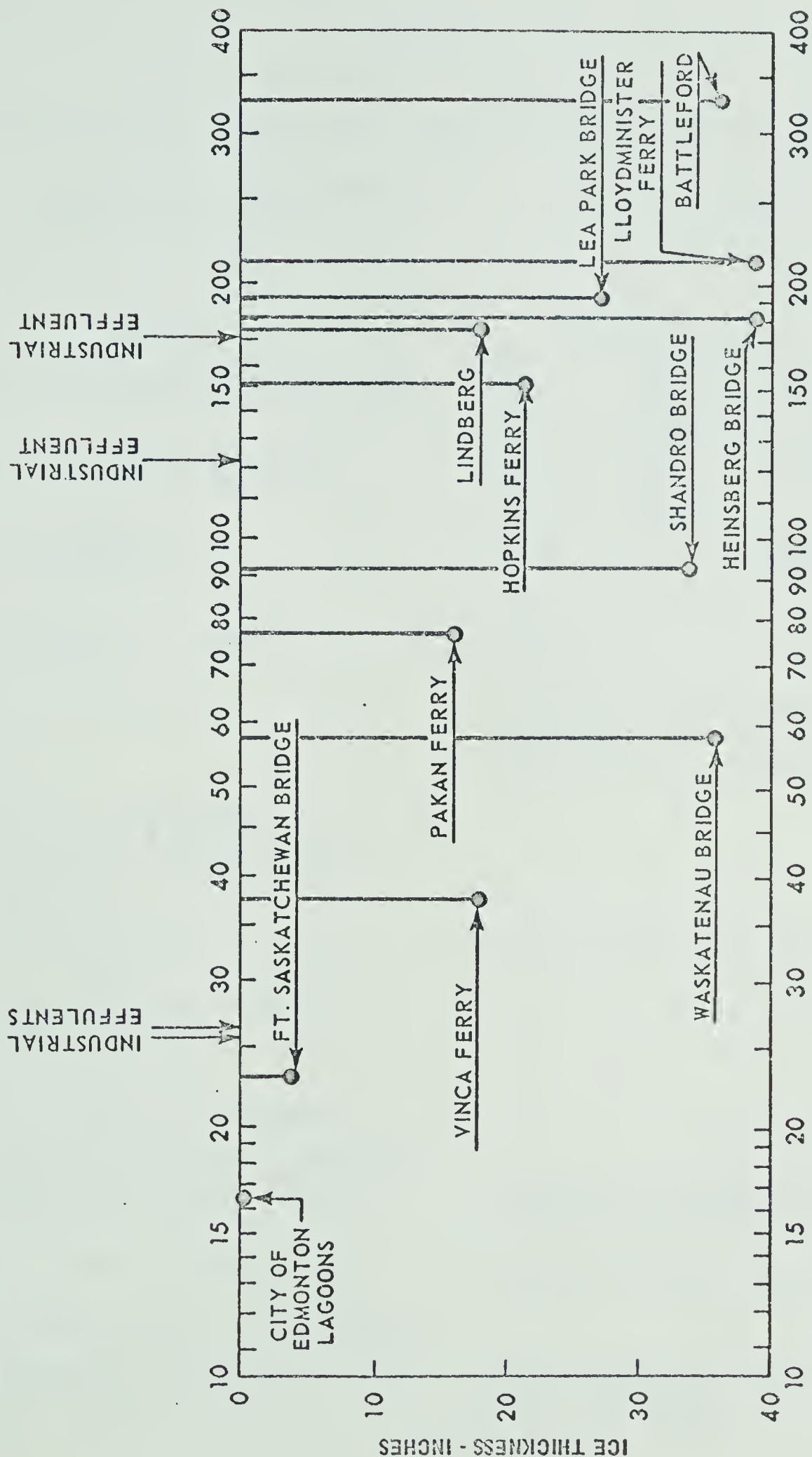
During the field investigation, ice thickness measurements were taken at various sampling locations (FIGURE 10).

5. River Usage

The North Saskatchewan River serves as a source of water supply for domestic consumption, agricultural and manufacturing processes and as a receiver and carrier of domestic and industrial wastes. Table II lists the major users of the North Saskatchewan River in the Province of Alberta.



FIGURE 9: NORTH SASKATCHEWAN RIVER NEAR CITY OF EDMONTON LAGOONS



DISTANCE DOWNSTREAM FROM LOW LEVEL BRIDGE AT EDMONTON-MILES

FIGURE 10: ICE THICKNESS ON THE NORTH SASKATCHEWAN RIVER - MARCH 1970



TABLE II

MAJOR USERS OF THE NORTH SASKATCHEWAN RIVER IN ALBERTA

(Information from Alberta Division of Environmental Health Services)

User	Purpose of Use
Town of Rocky Mountain House	Water supply, domestic waste disposal.
Town of Drayton Valley	Water supply, domestic waste disposal.
Town of Devon	Water supply, domestic waste disposal.
Imperial Oil - Devon	Industrial waste disposal.
City of Edmonton	Water supply, domestic waste disposal, cooling water for power plant, snow dumping.
Edmonton Industries	
Building Products Ltd.	
Imperial Oil Ltd.	
Texaco	
Union Carbide	Industrial waste disposal.
S & L Oil	
Gulf Oil Canada Ltd.	
Chemcell Ltd.	
Uniroyal Ltd	
City of Edmonton Lagoons	
Alberta Hospital - Oliver	
Edmonton Packing Plants	Domestic & industrial waste disposal (during summer mo.)
Sherwood Park	
Town of Fort Saskatchewan	Domestic waste disposal.
Fort Saskatchewan Industries	
Sherritt Gordon Mines Ltd.	Water supply, industrial waste disposal.
Dow Chemical Ltd.	

TABLE II - CONTINUED

User	Purpose of Use
Imperial Oil - Redwater	Water supply, industrial waste disposal.
Town of Redwater	Domestic waste disposal.
Town of Waskatenau	Domestic waste disposal.
Chemcell Ltd. - Duverney	Water supply, industrial waste disposal.
Town of Elk Point	Domestic waste disposal.
Canadian Salt Co. Ltd. Lindberg	Water supply, industrial waste disposal.

Because of its large population and industrial complex, the City of Edmonton is the source of the major pollution load to the North Saskatchewan River in Alberta. The main source is the domestic sewage effluents from the main and No. 3 sewage treatment plants. While the main sewage treatment plant provides primary treatment during the summer months and secondary activated sludge treatment during the winter months, the No. 3 sewage treatment plant provides primary treatment only. A summary of the effluent characteristics of these plants is shown in TABLE III and TABLE IV.

A series of sewage lagoons is located 16 miles downstream from the Low Level Bridge at Edmonton. These lagoons, constructed in an old gravel pit, receive domestic and packing house wastes from the northeast section of the City and domestic wastes from the hamlet of Sherwood Park, located immediately east of Edmonton. The lagoons, which store these wastes during the winter period, are drained during the summer months.

The Edmonton industrial complex, consisting mainly of the petroleum and chemical industries, use the North Saskatchewan as a source for cooling and process water, and as a receiver for industrial waste effluents. In the past, these industrial wastes have been the main cause of taste and odor problems found downstream from Edmonton.

TABLE III

EFFLUENT CHARACTERISTICS OF CITY OF EDMONTON

MAIN SEWAGE TREATMENT PLANT - 1969

(Data from City of Edmonton Engineering Department)

Month	Flow MIGD	SS lb/day	BOD lb/day	Grease mg/l	Phenols ppb	Coliforms MPN/100ml $\times 10^{-6}$
Jan.	27.67	21,000	16,100	33	12	3.9
Feb.	28.52	21,500	18,700	22	13	1.7
Mar.	32.27	47,400	29,300	21	6	0.8
Apr.	33.07	46,000	29,600	16	8	1.4
(a) May	31.38	55,600	52,800	30	46	13.0
June	31.59	64,400	66,900	96	79	-
July	34.35	71,000	64,100	71	75	10.9
Aug.	36.00	79,000	68,700	62	86	6.9
Sept.	37.16	69,800	64,000	31	43	30.2
(b) Oct.	32.19	52,600	33,800	26	14	3.1
Nov.	29.49	16,400	13,100	6	18	4.9
Dec.	28.66	12,100	11,200	24	19	5.4

(a) Secondary treatment terminated May 16, 1969

(b) Secondary treatment started September 30, 1969

TABLE IV

EFFLUENT CHARACTERISTICS OF CITY OF EDMONTON NO. 3

SEWAGE TREATMENT PLANT - 1969

(Data From City of Edmonton Engineering Department)

Month	Flow MIGD	SS lb/day	BOD lb/day	Grease mg/l	Phenols ppb	Coliforms MPN/100ml $\times 10^{-6}$
Jan.	2.31	1,880	2,000	34	52	14.0
Feb.	2.49	2,040	2,535	31	66	7.0
Mar.	2.80	3,540	2,785	50	48	26.1
Apr.	2.58	2,810	2,285	30	66	7.9
May	3.45	3,070	2,460	41	63	-
June	3.36	2,130	2,885	30	41	-
July	3.34	2,480	2,735	30	34	7.9
Aug.	3.27	2,670	2,620	25	29	68.8
Sept.	3.21	2,410	2,780	32	27	50.6
Oct.	3.60	3,869	2,610	18	41	15.1
Nov.	3.46	2,980	3,510	19	46	9.0
Dec.	3.42	2,280	3,535	50	29	7.6

Recreational use of the North Saskatchewan River in Alberta is restricted to boating and some sport fishing. There is no commercial fishing undertaken in the river in Alberta.

CHAPTER III

THEORETICAL CONSIDERATIONS IN STREAM ANALYSIS

1. Introduction

Since the classical work of Streeter and Phelps (1925), the theory describing the natural self-purification of streams has been subjected to continuous investigation and research by many workers. Today, mathematical models, numerical analysis and computers have become instrumental in the evaluation of the many physical, chemical and biological factors involved in the waste assimilation capacity of streams.

Before investigating the DO-BOD relationship pertaining to this study, a basic understanding of the interrelationship between the rates of oxygen utilization and reoxygenation, and the effects of: (1) sludge deposits, (2) biological extraction and accumulation, and (3) oxidation of nitrogenous substances to nitrates should be realized. A brief discussion of the theory, the basic relationships, and the latest research writings relating to waste assimilation in natural streams is presented in Appendix A.

This study is focused on the ability of the North Saskatchewan River, under ice-cover conditions, to satisfy the BOD of organic wastes discharged to the river, and to compare this BOD removal with the amount of dissolved oxygen used during a given time period.

2. BOD Removal from Streams

According to Streeter and Phelps (1925), the total BOD removed in streams was considered to be by oxidation of organic matter only. Since that time, it has been shown that organic matter can be removed by other means, such as sedimentation, biological extraction and accumulation and volatilization. On the other hand, BOD may be reintroduced into the stream water phase by scouring of bottom deposits. A further description of the many factors involved in the overall consideration of BOD removal from streams is outlined in Appendix A.

From the previous paragraph it can be seen that many factors are associated with the rate of removal of organic material from streams. In order to evaluate the rate of BOD removal from a stream, it is necessary to determine the BOD of river samples collected at successive locations downstream from the source of pollution. The travel time of any given slug of water from the source of pollution to the sampling stations must be known.

Eckenfelder and O'Connor (1961) have expressed the rate of removal of BOD from streams as:

$$K_r = \frac{1}{t} \log \frac{L_A}{L_B} \dots\dots (1)$$

where K_r is the rate of BOD removal (including all removal factors previously discussed), L_A and L_B are respectively the measured BOD at the upstream and downstream locations and t is the time required for the slug of water sampled at location A to reach location B.

3. Rate of Deoxygenation

The rate of oxidation of organic wastes in rivers depends on both the characteristics of the waste and the stream. The most important effect is that of temperature. Other factors to be considered, as outlined by Eckenfelder and O'Connor (1961) are: (1) turbulence which may increase contact opportunities between organic matter and bacteria, (2) biological growth on the stream bed which may increase the ability to extract and accumulate organic matter, (3) the immediate oxygen demand of some reducing substances present in the waste or stream, and (4) the lag effect if insufficient bacteria are available to assimilate the waste. Each of these effects has a direct influence on the concentrations of dissolved oxygen in the river.

The rate of deoxygenation in the stream, as outlined in Appendix A, may be expressed as:

$$K_d = \frac{1}{t} \log \frac{DO_A}{DO_B} \dots\dots (2)$$

where K_d is the rate of deoxygenation, t is the travel time of the sampled slug of water between locations A and B, and DO_A and DO_B are respectively the DO at locations A and B.

The evaluation of river rate constant (K_r) and the deoxygenation constant (K_d) will provide an indication of the type of BOD removal occurring within a given river reach. With the two rates being equal, BOD removal is considered to be by oxidation only. When the BOD removal rate (K_r) is greater than the deoxygenation rate (K_d), BOD may be removed by sedimentation and/or volatilization. On the other hand, if the deoxygenation rate is greater than the BOD removal rate, scouring and longitudinal mixing could be present.

4. Effect of Ice-Cover and Low Temperatures

The many physical, biological and chemical factors involved in the waste assimilation capacity of streams are greatly affected when under the influence of ice-cover conditions. Ice-cover forms a natural barrier to reaeration from the atmosphere, as well as effectively reducing photosynthetic and respiration activity of phytoplankton and aquatic plants. In essence, the dissolved oxygen required for organic matter stabilization and maintenance of the

aquatic environment is only available from that already present in the river and in any liquid wastes discharged into the stream.

With a decrease in temperature, both the rate of reaction and the oxidizability of organic matter are known to decrease. Fair and Geyer (1967) described the temperature effect on the rate constant and BOD by:

$$K/K_o = \theta_k (T-T_o) \dots \quad (3)$$

$$L/L_o = \theta_L (T-T_o) \dots \quad (4)$$

where K is the rate constant, θ is the temperature coefficient, T is the temperature and L is the BOD. The subscript zero denotes the referenced values of K, L and T .

Briggs (1966) in studying long term, low temperature BOD, confirmed that the deoxygenation rate constant (K) and the ultimate first stage BOD decreased significantly at lower temperatures of 0-5°C. He found the rate constant (K) for domestic sewage at 20°C was 0.139 per day; while at 0°C it was of the order of 0.043 per day.

CHAPTER IV

FIELD AND LABORATORY STUDY AND PROCEDURES

1. Purpose

This study was undertaken in an attempt to correlate and possibly formulate the relationship between DO utilization and BOD removal in the North Saskatchewan River under ice cover. A slug of water would be followed from Edmonton to Battleford, Saskatchewan and values of DO and BOD obtained at various sampling locations (FIGURE 11).

Foremost in a study of this kind are the time-of-travel measurements required to determine the mean velocity of streamflow for various winter discharges.

2. Velocity Determination

Within the past decade, fluorescent dyes have proven to be an excellent tracer in studies of movement of soluble contaminants in natural streams and have generally replaced other tracers such as chemical salts and radioisotopes. Pritchard and Carpenter (1960) first used this method in measurements of diffusion in estuarine and inshore waters.

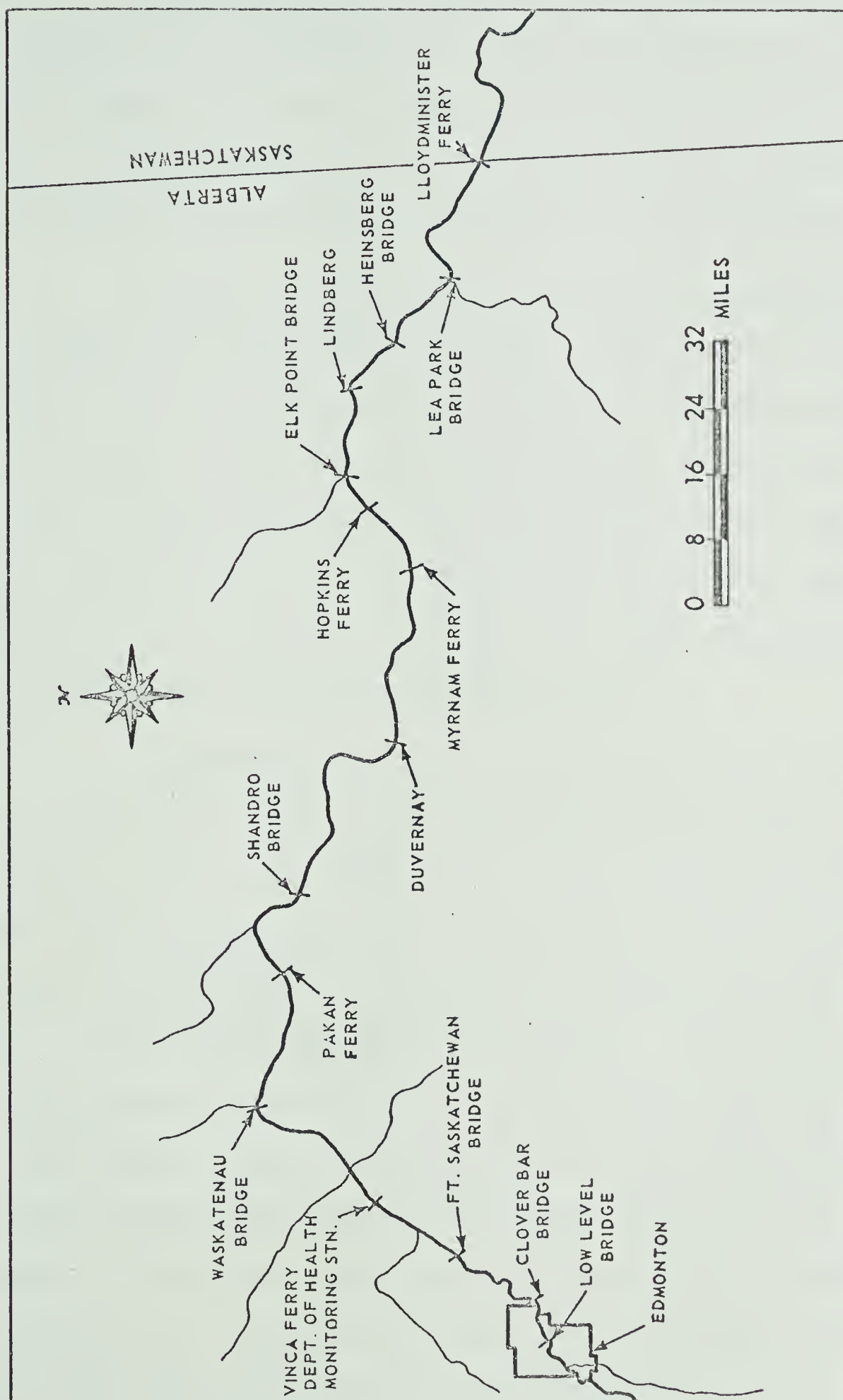


FIGURE 11: SAMPLING SITES USED DURING STUDY PROGRAM

The object of a time-of-travel measurement is two-fold: (1) to determine the time it takes for a mass of water tagged with dye to travel downstream from one location to another, and (2) to determine how the stream dilutes and disperses the soluble contaminant in the process.

In this study, dye was injected instantaneously as a slug. At downstream locations, grab samples taken at frequent time intervals were tested in a fluorometer for dye presence. Time-concentration curves, similar to Figure 12, were drawn and the time between peak concentration was considered to be representative of the mean time-of-travel in a reach. Generally, the time-concentration plots resemble skewed bell-shaped curves.

Fluorescence, which is essentially the instantaneous emission of light from a molecule or atom which has absorbed light, was measured by a G.K. Turner Associates Model III Fluorometer. This fluorometer is basically an optical bridge which is analogous to a Wheatstone Bridge used in measuring electrical resistance. The optical bridge measures the difference between the light emitted by the sample, which is proportional to the concentration of fluorescent material in the sample, and that from a separate calibrated light path. The quantity of light required in the calibrated light path to balance with that from the sample is automatically indicated on a dial marked in 100 equal divisions. The fluorometer is equipped with

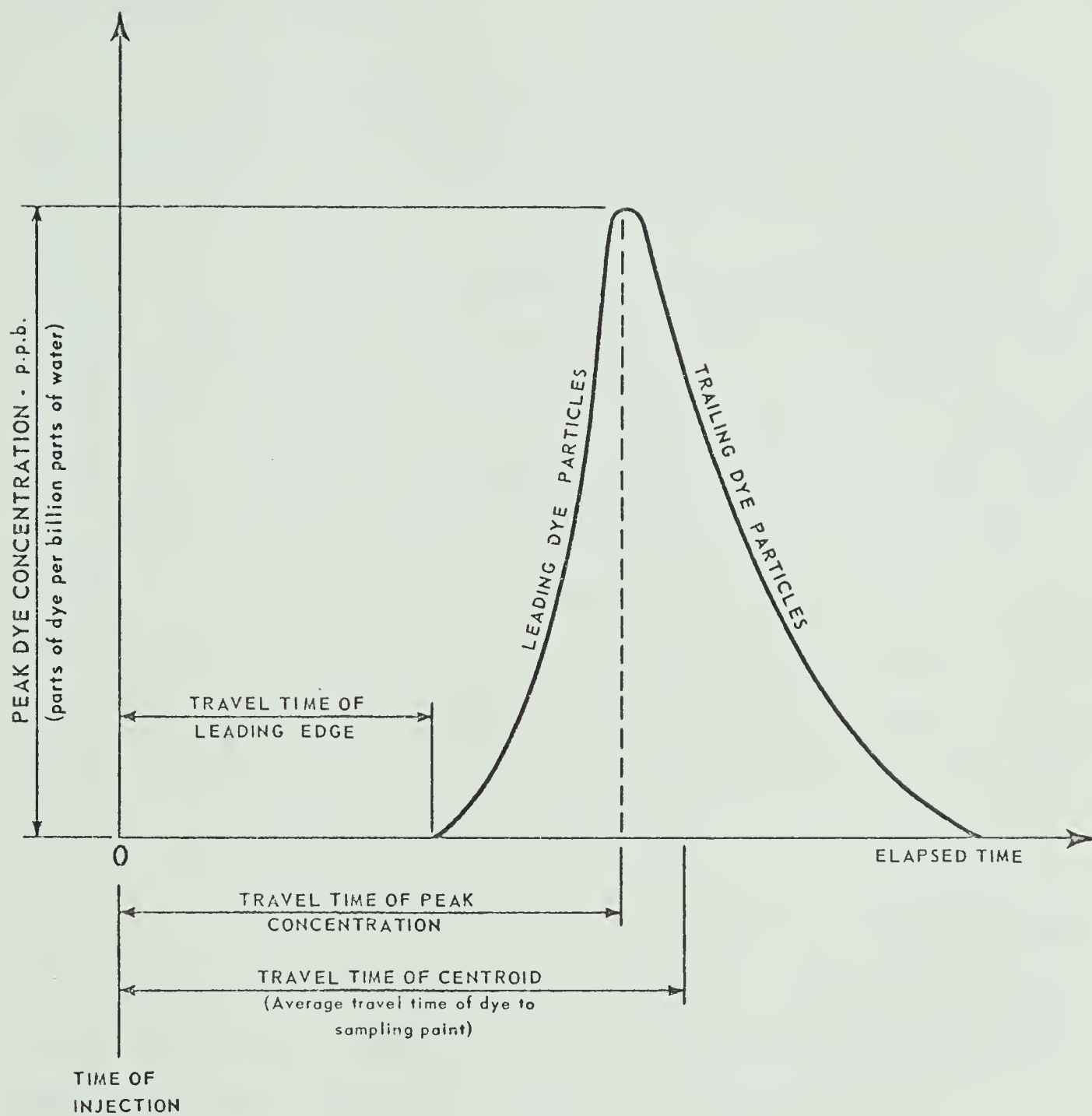


FIGURE 12: TYPICAL TIME - CONCENTRATION CURVE

four openings or apertures, which emit light to the sample in the approximate ratio of 1:3:10:30. This provides means for examining wide ranges of concentrations without changing the filter arrangements.

The purpose of color filters in a fluorometer, as stated by Wilson (1968), is to limit the light reaching the photomultiplier as far as possible, to that fluoresced by the dye. Further he based filter selection on : (1) the useful output spectrum of the lamp, (2) the spectral fluorescent characteristics of the dye, (3) potential interference from fluorescence of materials present in the stream, and (4) potential interference from light scattered by the sample. The desired wave length of light required to excite the sample is selected by the primary filter located between the light source and sample, while the wave length of light to be measured is selected by a secondary filter located between the sample and photodetector.

The two commercial dyes used in this study were 25% (by weight) fluorescein and 40% (by weight) rhodamine B dye solutions. Some of the physical properties of the dyes and their costs are compared in TABLE V.

Maximum optical absorbence of fluorescein occurs at a wave length of 480 mu and maximum fluorescent intensity occurs at 510 mu. The filters recommended by G.K. Turner Associates for fluorescein are a combination of Wratten 2A

TABLE V

COMPARISON OF FLUORESCENT DYES USED IN TIME-OF-TRAVEL STUDIES

	Rhodamine B	Fluorescein
Dye Color	Basic Violet 10	Acid Yellow 73
Formula	$C_{28}H_{31}N_2O_3 \cdot Cl$	$C_{20}H_{12}O_5$
Form Used in Field	40% Solution (by weight)	25% Solution (by weight)
Specific Gravity	1.12	1.11
(a) Cost/lb in Given Form	\$2.23	\$0.67
Strong Points	(1) Very high detectibility (2) Moderate cost	(1) Inexpensive (2) Low sorptive tendency (3) Low temperature effect
Weak Points	(1) Fair diffus- ivity (2) Moderate sorptive tendency (3) Moderate rate of photo- chemical decay (4) High acidity of solutions	(1) Very high photo- chemical decay rates (2) High potential interference by background

(a) Cost per pound of solution includes total cost delivered to the University of Alberta.

and 47B (peak at 436 mμ) for the primary and a combination Wratten 2A and 12 (peak at 510 mμ) for the secondary.

Feuerstein and Selleck (1963) recommended one Corning glass color filter of Color Specification No. 7-83 for the primary filter and the secondary filter to consist of one each Corning glass filter of Color Specification Nos. 3-70 and 4-97.

Maximum optical absorbence of rhodamine B occurs at a wave length of 550 mμ and maximum fluorescence intensity at 570 mμ. The filters recommended by G.K. Turner Associates were a special primary filter combination with a peak Color Specification of 546 mμ and the secondary filter combination peaking at 590 mμ. This is a general purpose filter combination supplied with the instrument. Feuerstein and Selleck (1963) recommended two Corning glass color filters of Color Specification No. 1-68 and one Wratten No. 61 gelatin filter for the primary, the secondary filter to consist of one each Corning glass filter of Color Specification Nos. 3-66 and 4-97. This filter system is essentially the same recommended by the manufacturer.

Prior to usage of the fluorometer in the field, the necessary filter requirements and the relation of the fluorometer readout (dial readings) to dye concentrations was determined for each of the dye solutions. Using river water as diluent, known standard concentrations were made

for each dye solution through a series of dilutions. These standards were stored at 0°C in narrow mouth, amber glass bottles.

Feuerstein and Selleck (1963) investigated the temperature effects on several fluorescent tracers and reported that sample temperatures had a marked effect on rhodamine B and a much lesser effect on fluorescein. They showed that fluorescent activity increases (resulting in higher readings) as temperature drops. The temperature of 0°C, which was the temperature of the North Saskatchewan River under ice cover, was selected as the base temperature for fluorometer calibration. All fluorometer laboratory and field samples were tested at 0°C to eliminate the need to apply temperature correction factors.

The aforementioned filter recommendations plus other combinations were tried for each of the known standard concentrations. Optimum response to fluorescein was obtained by using a single Wratten 47 B (peak at 440 mμ) primary filter and a combination of Wratten 2A and 15 (peak at 520 mμ) for the secondary filter. Also it was determined that the recommended 546/590 filter combination was most suitable for rhodamine B.

The fluorometer was calibrated by determining, on all four ranges, the average of a series of three dial readings for each known concentration. Each dial reading

was corrected for normal river background. Calibration curves, FIGURE 13 and FIGURE 14, were constructed by plotting the average dial reading against the corresponding dye concentration. A one percent neutral-density (ND) filter, which passes only one percent of the light falling on it, was used when very high concentrations forced the fluorometer dial off scale. These calibration curves illustrate the linear relationship between dial readings and dye concentrations. A calibration constant for each curve was determined by dividing each concentration (C) by its corresponding corrected dial reading (D) and averaging the C/D values. Thereafter, sample dye concentrations were determined by multiplying corrected dial readings (sample minus background readings) by the calibration constant corresponding to the range on which the sample was measured.

To maintain continuity between laboratory and field fluorometer readings, a 100 - 130/115 volt Bausch and Lomb voltage stabilizer was used with the fluorometer. It was found that with stable line voltage and proper filter selection, concentrations as low as 0.5 ppb could be readily detected. All measurements were made using the general purpose ultraviolet lamp and the standard cuvette holder door supplied with the instrument. Cuvettes used were round borosilicate glass 12mm x 75mm culture tubes. The instrument was zeroed by using a round black 12 x 75mm dummy cuvette to simulate a completely nonfluorescent sample.

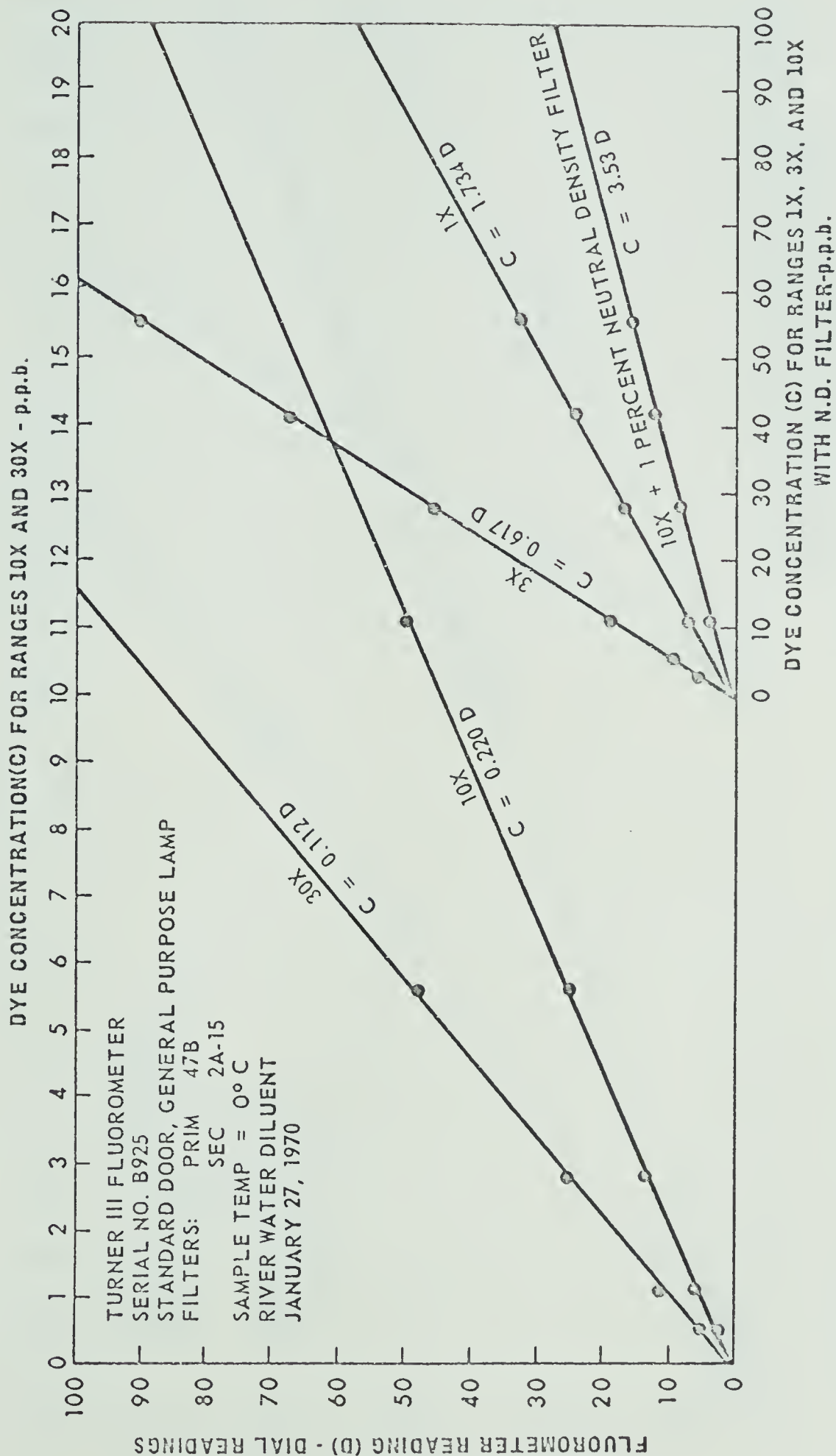


FIGURE 13: CALIBRATION CURVE - 25% FLUORESCIN DYE SOLUTION

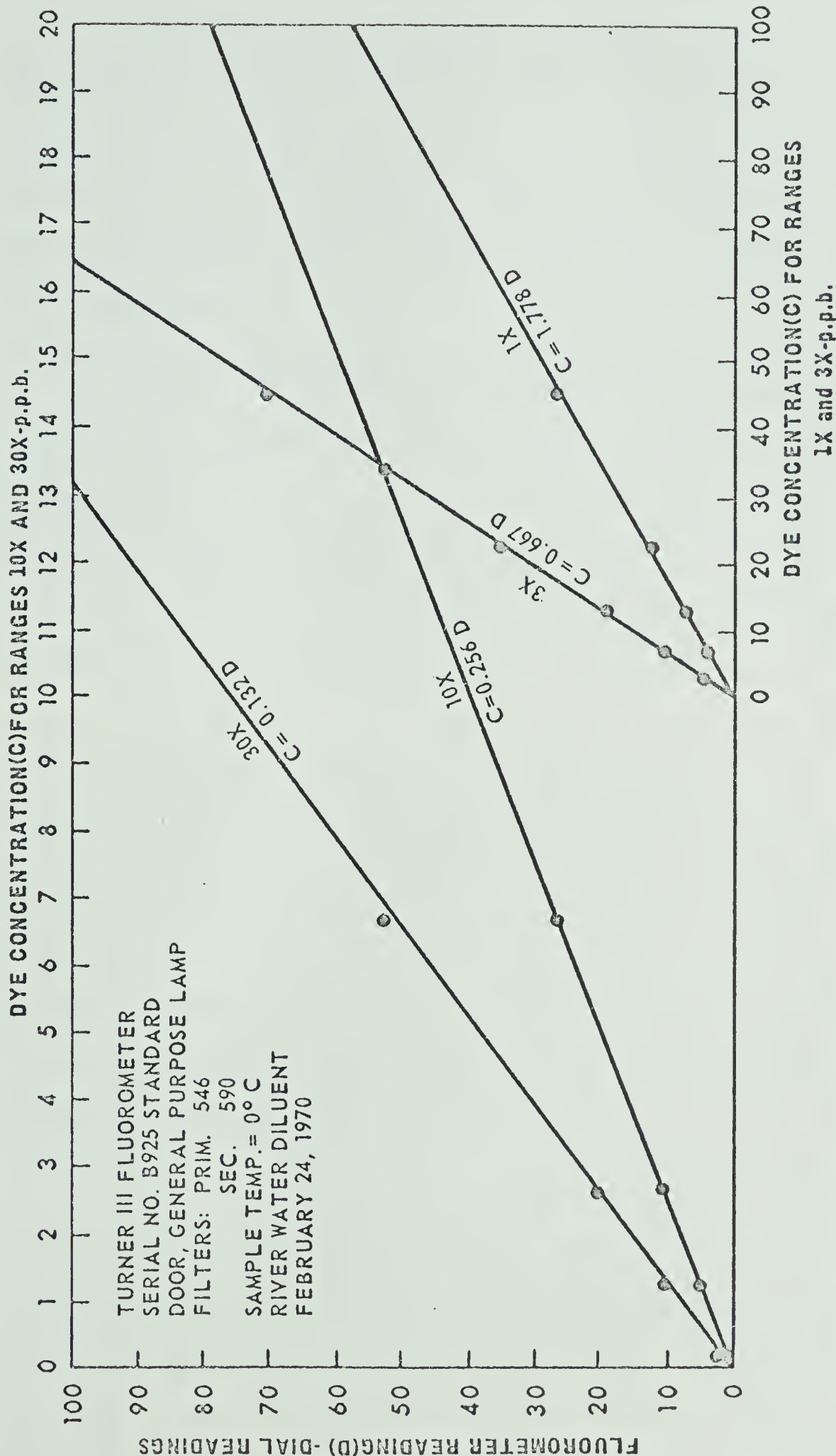


FIGURE 14: CALIBRATION CURVE - 40% RHODAMINE B DYE SOLUTION

Two sources of power, a Terado model No. 50-191, input 12V DC - output 110 VAC, power inverter and a Honda model ED300, 300 watt portable generator were used for field operation of the fluorometer. FIGURE 15 shows the fluorometer set up in the laboratory with the voltage stabilizer and power inverter.

Four dye tracing runs were conducted using 25 per cent fluorescein and 40 per cent rhodamine B dye solutions in each of two runs. Initial concentrations in the river were determined from the weight of dye injected and the estimate of river discharge at the time of injection. Sampling locations were chosen with regard to accessibility and ease of sampling. At each location, with the exception of locations where raw water intake lines were used, samples were taken through the ice directly over the main river channel. Samples were taken at 15-20 minute intervals until the wave arrived then every 5 minutes until it was established that the wave peak had passed by. Sampling of 15-20 minute intervals was then continued until a reasonable wave pattern was established.

The initial dye injection was made at 2300 hrs. on January 27, when approximately 50.6 lbs of 25 per cent fluorescein dye solution was introduced into the Sherritt Gordon effluent line at Fort Saskatchewan. Samples were collected at the Department of Health water quality monitoring station at Vinca, located 12.5 miles downstream

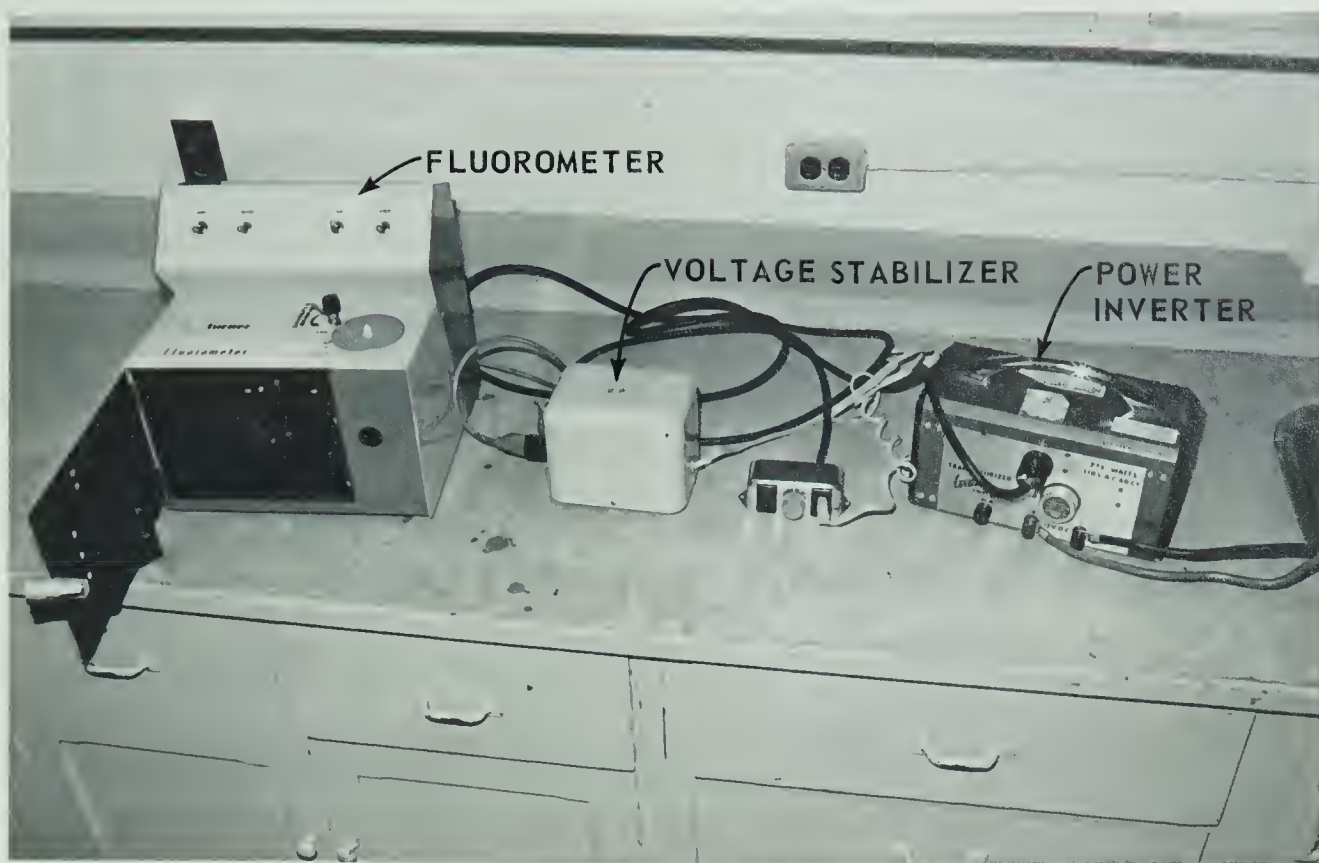


FIGURE 15: FLUOROMETER AND RELATED EQUIPMENT.



FIGURE 16: RHODAMINE B DYE SOLUTION PRIOR TO INJECTION

from Sherrit Gordon, and at the Waskatenau Bridge located 32.3 miles downstream from Sherrit Gordon. The peak concentrations arrived at Vinca approximately 14 hours after injection and at Waskatenau approximately 38.5 hours after injection. The discharge during this run was approximately 2390 cfs and the initial concentration upon injection was 283 ppb.

The initial dye run was used not only as a time-of-travel study but as a trial run to develop sampling techniques and to gain familiarization with equipment. At Vinca a 120 VAC power outlet was available but the power inverter was required at Waskatenau. Sampling commenced an hour before the estimated time of peak arrival, which was based on the travel time from Fort Saskatchewan to Vinca. To protect the electronic circuitry, the power inverter is restricted to a maximum of 5 hours of continuous operation. It was during the later stage of this time limit that the wave arrived and the power inverter had to be shut down before the peak had arrived. Samples were then collected every fifteen minutes and kept in 2 oz narrow mouth, amber polyethylene bottles. The samples were then tested in the laboratory the same evening. Due to the operating restriction of the power inverter, the Honda generator was rented to provide a longer running power source.

The second dye tracing run was carried out between Edmonton and Fort Saskatchewan when 49.4 lbs of 25 percent

fluorescein dye solution was released into the No. 3 Sewage treatment plant (STP) effluent at 0155 hrs on January 31st. To eliminate the possibility of photochemical decay of the fluorescein dye cloud while in open water, the test was conducted partly during the night hours and during a period of heavy overcast skies. Sampling was carried out at the Low Level, Capilano, and Clover Bar Bridges and at the Sherrit Gordon water treatment plant in Fort Saskatchewan. It was originally planned to sample at the Fort Saskatchewan Bridge but a severe snowstorm precluded sampling at that location. The discharge during this run was 2500 cfs with the initial dye concentration of 264 ppb at the No. 3 STP dropping to less than 2 ppb at Sherrit Gordon in a total distance of 27.1 miles.

Another run was conducted over a stretch of 26.6 miles when 35.3 lbs of 40 percent rhodamine B dye solution was injected at Hopkins Ferry at 1203 hrs on February 24th. Samples were taken downstream from the Elk Point and Heinsberg Bridges. With an estimated discharge of 2930 cfs, the initial concentration was 1.29 ppm.

The fourth run commenced at 0001 hrs February 26th when 32.9 lbs of 40 percent rhodamine B dye solution was injected through the ice at the Heinsberg Bridge. The estimated discharge was 2930 cfs resulting in an initial injected concentration of 1.20 ppm.

In the first two runs the 25 percent fluorescein dye solution, available in 5 gallon pails, was poured directly into a sewer effluent line. In the final two runs, the 40 percent rhodamine B dye solution had to be introduced through the ice directly into the main channel stream. This problem is further compounded because rhodamine B dye solution is only available in 125 lb drums and must be subdivided into lesser amounts for individual dye tracing tests. Cameron (1967) introduced dye into one hole and forced it under the ice by pumping river water from another hole upstream. To eliminate the necessity of renting a higher voltage power generator and pumping equipment, another method of introduction was conceived and found to work very well.

Approximately 30-35 lbs of 40 percent rhodamine B dye solution from the bulk drum was poured into each of two heavy polyethylene bags, knotted at the top and then secured with a length of rope. The weight of each bag was noted and then stored in the empty 5 gallon fluorescein pails for transport to the field. At the point of injection a hole large enough to receive a bag of dye was cut into the ice directly over the main river channel. FIGURE 16 shows a bag of dye being lifted from the pail, prior to injection through the ice at Hopkins Ferry. The bag of dye was then lowered through the ice, by the length of rope

attached to the bag. The bag readily sank because of the higher specific gravity (1.12) of the dye solution. When it was established that the bag of dye was at sufficient depth, a long handled ice chisel was used to pierce the polyethylene bag to release the dye solution. Complete injection of the dye took less than 1 minute.

3. Dissolved Oxygen Monitoring and Recording

In a study such as this one, it would be advantageous if one could attain continuous monitoring and recording of dissolved oxygen levels at any given location on the river. To do this a Union Carbide Model 1101 dissolved oxygen analyzer and a Leeds and Northrup Speedomax M (Mark II) recorder were purchased.

The Union Carbide dissolved oxygen analyzer consists of a probe and control cabinet interconnected by a three-conductor shielded cable (FIGURE 17). The plastic probe assembly contains a thallium electrode, reference electrode and a temperature-sensitive resistor. The control cabinet encloses a solid-state operational amplifier and power supply which compensates for water temperature changes and linearizes the cell output signals which are displayed on a meter. This instrument will monitor and record DO levels from 0-15mg/l and water temperatures from 0-50 degrees centigrade. A 110 VAC power source is required for the analyzing and recording operation.

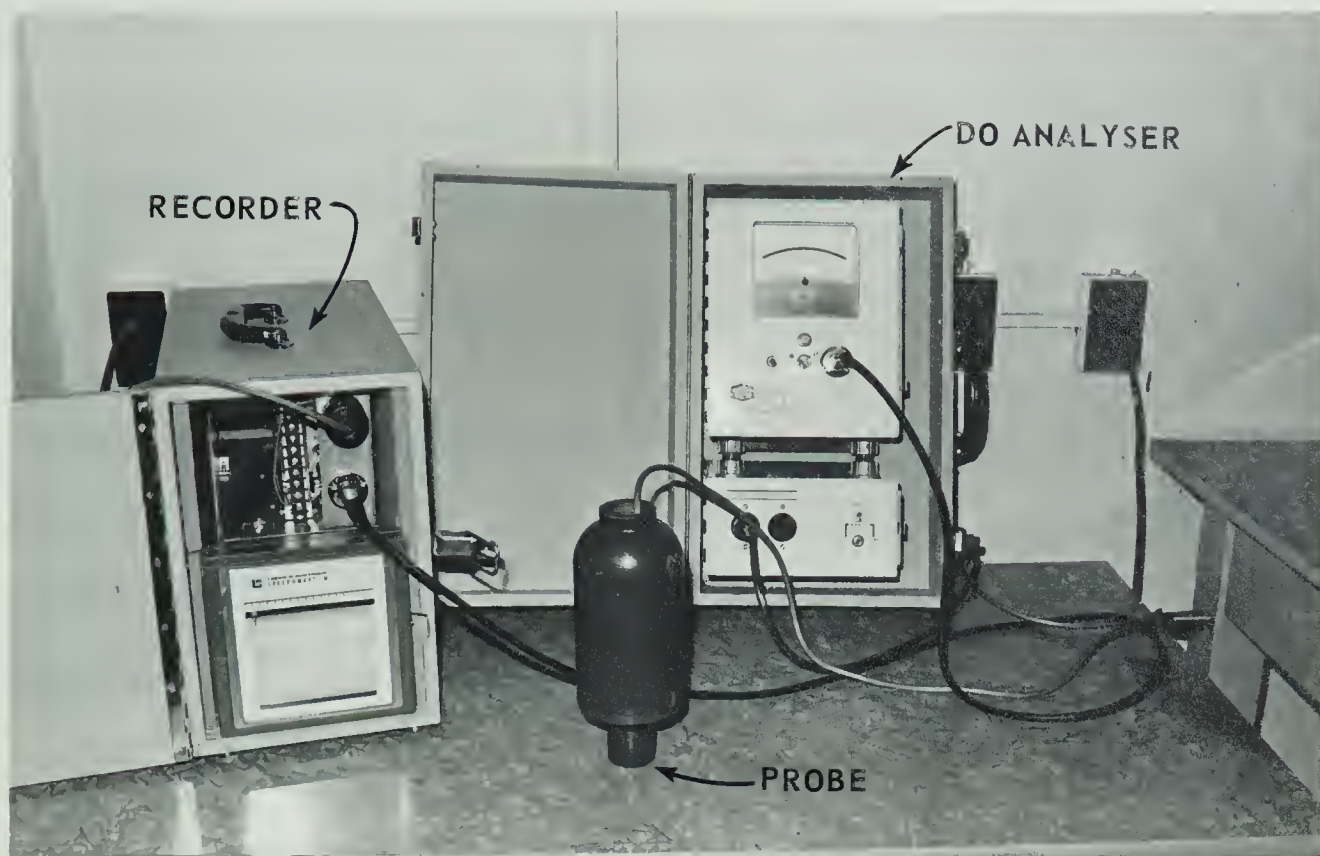


FIGURE 17: DISSOLVED OXYGEN ANALYSER AND RELATED EQUIPMENT.



FIGURE 18: DISSOLVED OXYGEN SAMPLING CAN.

The DO concentrations are determined by measuring the voltage potential developed, in relation to the reference electrode, when oxygen in the water reacts with the thallium electrode according to the following reaction:



The nature of the reaction is such that as the DO concentrations increase the signal decreases. The cell output changes logarithmically with changes in DO and the analyzer's electronic circuitry converts this output to that of a linear function, which is displayed on the meter.

The temperature-sensitive resistor and its associated electronic circuitry compensates cell output for temperature changes and provides a signal for water temperature readings.

The analyzer provides a 0-50 mv linear output to the recorder, which is calibrated to provide continuous DO and temperature records on a 4 inch chart. The analyzer was fitted with a DO temperature timer-activated switching unit which provided alternate recording of DO and water temperature on the single pen chart recorder.

Prior to commencement of field work, considerable time and effort was expended in trying to calibrate the probe, analyzer and recorder to predetermined DO and temperature levels. As outlined by the manufacturer's literature, the calibration was started with the probe in an agitated

water bath. The electronic circuitry and cell output was monitored on a digital voltmeter. Dissolved oxygen levels in the water bath were continually checked by the Azide Modification of the Iodometric Method, as outlined in Standard methods (1965). With the probe in agitated water, insufficient and unsteady cell output was noted even though DO concentrations remained constant. Further experimentation showed that, for reliable and steady cell output, a considerable flow velocity past the probe was required.

Calibration efforts were continued in the Hydraulics Laboratory where the threaded plastic probe, containing the electrodes, was connected to a water supply line by means of a 1-inch by 1-inch by 1/2 inch plastic T. A portable 10 usgpm pump was used to supply and return water from a small reservoir. Consistent cell output was obtained only when the pump operated at full capacity. The analyzer and recorder were then calibrated using this enclosed pumping system.

Because the analyzer was restricted to flows in excess of 4 fps, the monitoring and recording of DO temperature levels in the river can only be obtained by using raw water supply lines. Several water supply lines are located in the vicinity of Edmonton, with single supply lines located at Fort Saskatchewan, Redwater, Duvernay, Lindberg and North Battleford. The Alberta Division of

Environmental Health Services maintained constant DO recording at their Vinca monitoring station, located approximately 30 miles downstream from Edmonton and at Lindberg, located approximately 165 miles downstream.

The feasibility of installing the equipment at the North Battleford Water treatment plant pump house was investigated. However, the city draws the bulk of its water supply from wells and was utilizing the river supply only 4 hours per day. This precluded the use of this location as a monitoring site since continuous flow past the probe is required for reliable records.

For the purpose of this study, the only remaining location which could provide meaningful results would be directly upstream from any waste effluents being discharged to the river at Edmonton. On January 15 the probe was connected to the raw water intake line in the No. 2 pump house, which supplies cooling water to the Edmonton power plant (FIGURE 7). The DO analyzer and recorder were in operation from January 15 to March 4 and during this time additional problems were noted. A summary of the major problems encountered, together with comments regarding future usage of this equipment, can be found in Appendix B.

4. Dissolved Oxygen Survey

Samples for field determination of DO were collected in a standard 300 ml BOD bottle, which was contained in a sampling can similar to that described in Standard Methods (1965). The sampling can (FIGURE 18) was sized to fit through an eight inch hole in the ice and was of sufficient weight to ensure that the sample consisted of water from the main channel flow.

A portable field test kit was made up to enable DO determination as soon as the sample was obtained. The Azide Modification of Iodometric Method, as outlined in Standard Methods (1965), was used for all DO tests. Temperature and barometric pressures were noted and recorded for each DO sample.

5. Biochemical Oxygen Demand Determinations

Values for 5 day, 20°C BOD (BOD-5-20) were obtained by following the method outlined in Standard Methods (1965). Field samples were stored in chromic acid-cleaned 64 oz glass bottles and kept in sub-freezing temperatures in the back of the truck. All field samples were set up for BOD testing on the day of collection. Field samples gathered in the vicinity of Edmonton were returned to the laboratory for setting up and incubation, while samples gathered at locations removed from Edmonton were set up at the place of lodging and stored in specially constructed

boxes designed to hold 12 BOD bottles. Provision was made to maintain the room temperature at $20 \pm 1^{\circ}\text{C}$ and every effort was made to maintain the vehicle temperature at 20°C when the boxes were returned to the university incubator. The period of transport from the field to the university never exceeded 4 hours, thus ensuring minimum deviation from the required $20 \pm 1^{\circ}\text{C}$ incubation temperature.

The samples, stored in the 64 oz glass bottles, were warmed to 20°C , agitated to remove excess dissolved oxygen and set up in four BOD bottles. One bottle was used to determine the initial dissolved oxygen and the remaining 3 were incubated at 20°C for 5 days, at which time BOD tests were made.

6. River Discharge

For the purpose of this study, knowledge of river discharge at any given time was essential in order that: (1) velocities determined from time-of-travel measurements could be related to the river discharge at the time of dye tracing, (2) the initial concentration of the soluble contaminants (fluorescent dyes) could be determined, (3) it could be ascertained that relatively stable flows would occur during time-of-travel studies, (4) the applicable velocity corresponding to the discharge at the time of DO - BOD sampling would be used, and (5) the expected river BOD loadings from various industrial and domestic effluents could be calculated.

An accurate, 24-hour stage recording and telemetering station, operated by the Water Resources Branch of the Federal Department of Energy, Mines and Resources, is located at the Low Level Bridge in Edmonton. The river stage (gage height), at any given time, may be obtained by telephone and the river discharge ascertained from readily available stage-discharge curves (FIGURE 19). The stage-velocity curve for this gauging station is shown on FIGURE 20.

The river discharges corresponding to the time-of-travel studies were extrapolated from the records of average daily discharge maintained by the Water Resources Branch. Based on the average measured velocity, the time required for a slug of water passing through Edmonton to reach the point of injection was determined. This travel time (in days) was subtracted from the date of injection to find the date when the measured slug of water passed through Edmonton. The average daily discharge corresponding to the date the slug was in Edmonton was considered to represent the discharge at the time of dye tracing. Discharges for any particular day during the winter months did not vary more than 100-200 cfs, thus the aforementioned procedure would give a reasonably good estimate of the discharge corresponding to any given time-of-travel study.

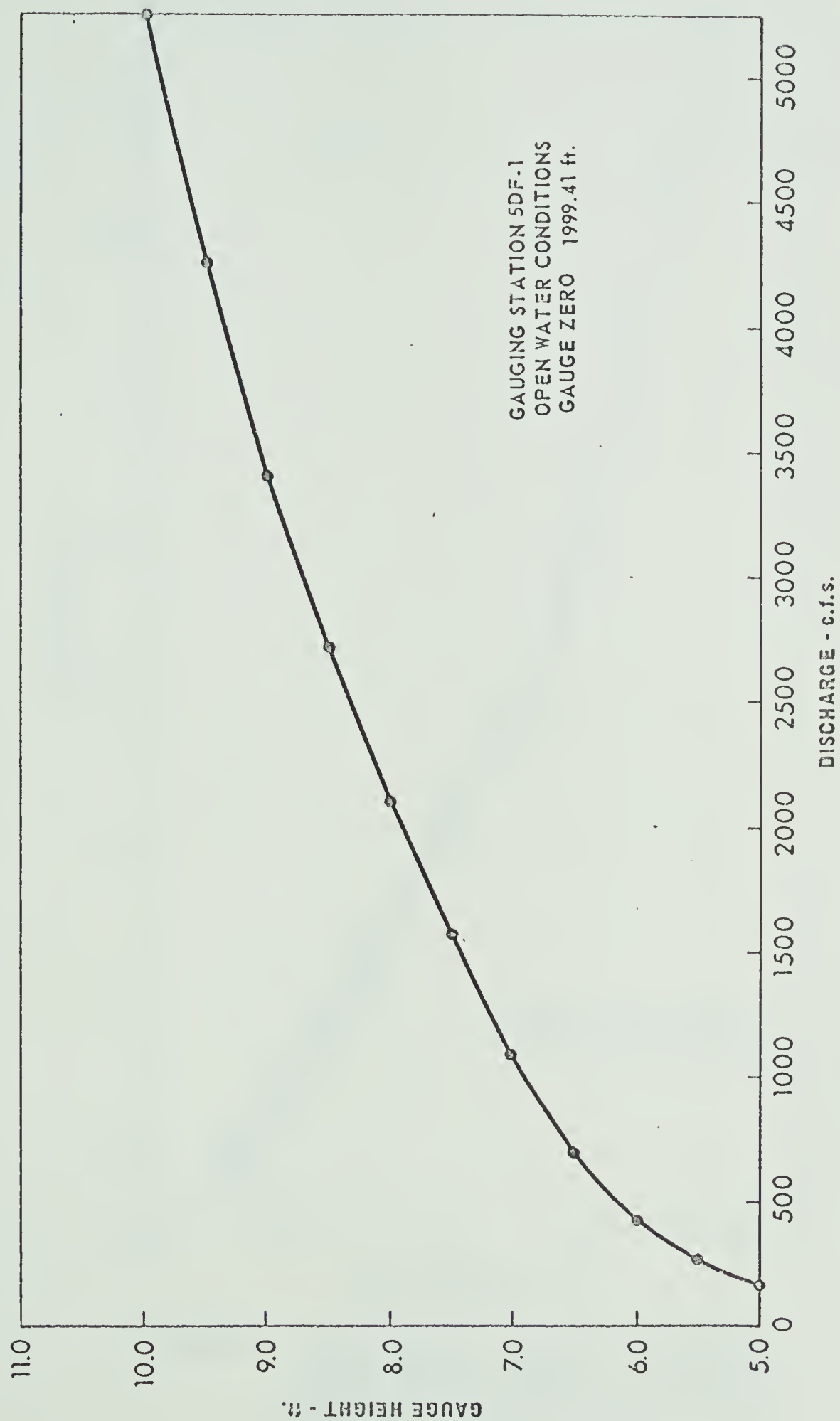


FIGURE 19: STAGE - DISCHARGE CURVE FOR NORTH SASKATCHEWAN RIVER AT LOW LEVEL BRIDGE
EDMONTON (data from Federal Department of Water Resources)

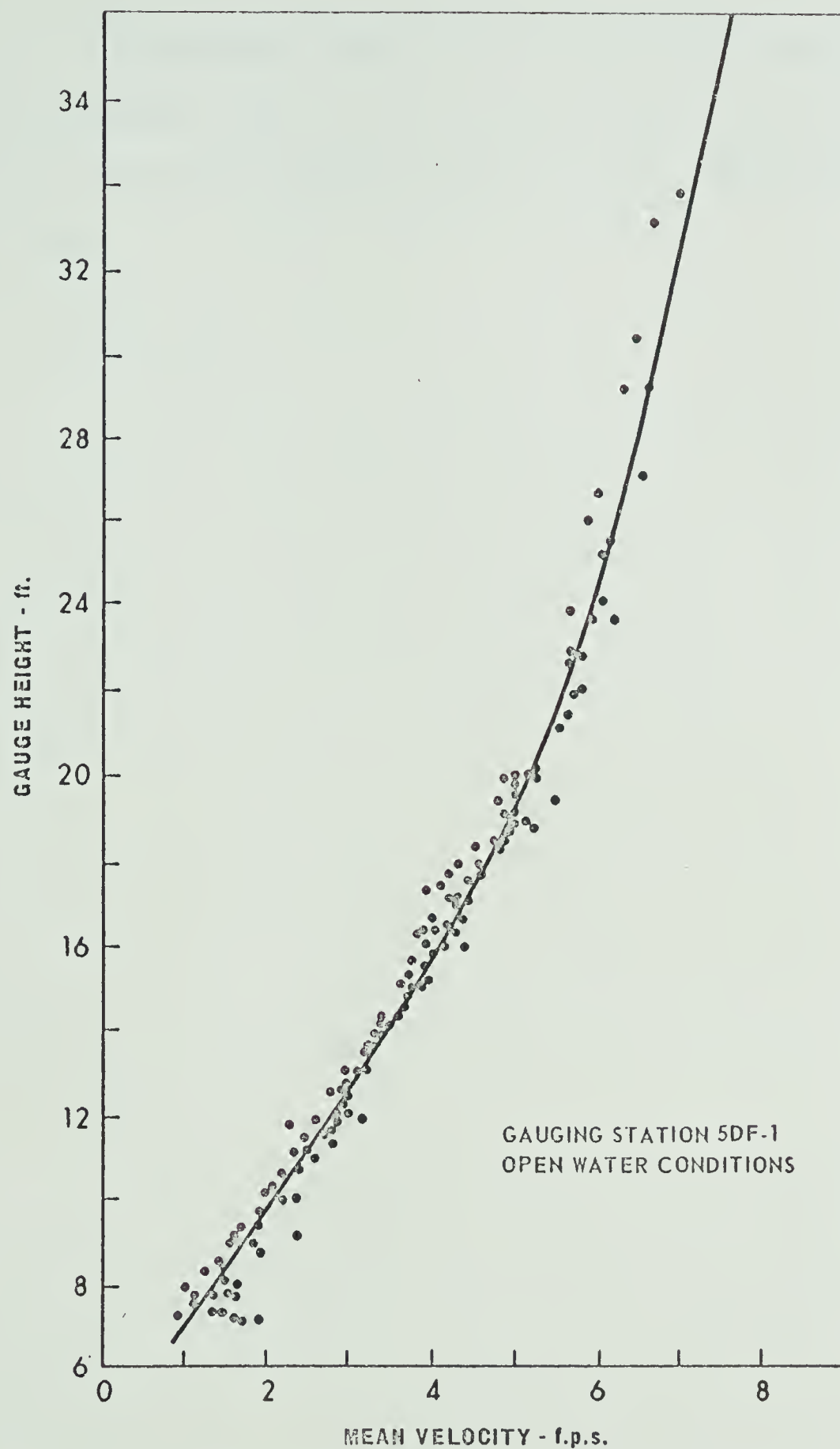


FIGURE 20: STAGE-VELOCITY CURVE FOR NORTH SASKATCHEWAN RIVER AT LOW LEVEL BRIDGE - EDMONTON (data from Federal Department of Water Resources)

Discharges during the DO and BOD sampling runs, which commenced from the Low Level Bridge, were determined directly from the gauging station at the commencement of each run.

CHAPTER V

TIME-OF-TRAVEL ANALYSIS

1. Introduction

Foremost in a study of deoxygenation in streams is the ability to predict reasonable flow velocities corresponding to various discharges within any given reach. The rate constants involved in the waste assimilation capacity of streams are time dependent and an accurate determination of these rates requires a reasonable estimate of the travel time between any two consecutive sampling locations. Due to diurnal fluctuations of DO levels in the river under ice cover, the travel time of a sampled slug of water between successive downstream locations is necessary if representative samples are to be obtained.

The Alberta Division of Environmental Health Services maintains continuous monitoring and recording of river DO concentrations at Vinca and Lindberg. These records show that, for normal winter flows under ice-cover conditions, the difference between the maximum and the minimum DO concentrations in the river on any given day varies from approximately 0.5 to 1.0 mg/l. The diurnal

fluctuation in DO concentration at Vinca for the days that DO-BOD samples were taken is illustrated in FIGURE 21.

To reliably predict a flow velocity which would correspond to any given discharge under ice-cover conditions, an extensive time-of-travel survey carried out over an entire winter period would be required. This survey would involve time-of-travel measurements at various known discharges in all reaches within the study area. The magnitude and scope of this survey would require many investigators. Because ice formation conditions vary from year to year, the results of this particular survey may be limited to the winter period in question.

For the purposes of this study, several assumptions were made regarding the flow velocities within the study area. The time available prevented an extensive time-of-travel measurement program. Consequently, four travel time studies, using fluorescent dyes as a tracer, were carried out at different discharges in various reaches throughout the study area. It was assumed that these four studies would be representative of the flow velocity for a given discharge, during the entire period of investigation and a plot of these results could be used to predict flow velocities at other discharges. It was further assumed that steady, uniform flow conditions were found throughout the study area. This then implied that (1)

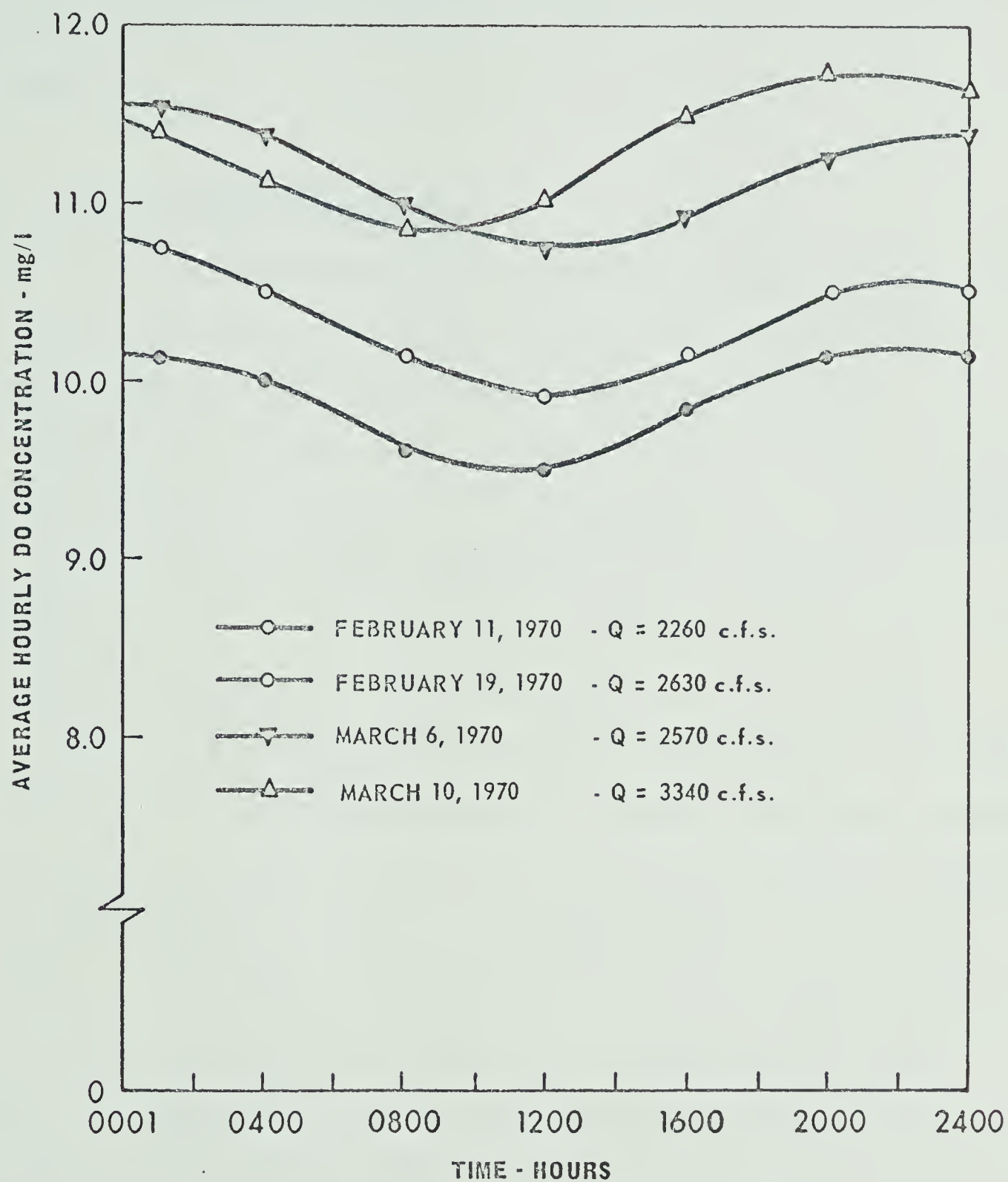


FIGURE 21: DIURNAL FLUCTUATIONS IN THE NORTH SASKATCHEWAN RIVER AT VINCA FERRY (data from Alberta Division of Environmental Health Services)

the depth, water area, velocity and discharge at each section of the channel reach are constant and (2) the energy line, water surface and channel bottom are all parallel.

2. Dye Tracing Measurements

Four separate time-of-travel studies, using fluorescent dye as a soluble contaminant tracer, were undertaken in various reaches between Edmonton and Lloydminster Ferry. The results of these runs are shown graphically in FIGURES C1 to C4 (Appendix C). The results of these time-of-travel studies are also summarized in TABLE VI. The time required to completely inject the fluorescent dye into the main channel flow was needed in order to estimate the initial dye concentration in the river and to establish the peak-to-peak travel time between the point of injection and the downstream sampling location. In dye runs Nos. 1 and 2, a 5 minute period was used to empty the 5 gallon pails of 25% fluorescein dye solution. In using the Sherritt Gordon sewer outfall line in run No. 1, a time of 11 minutes was required for the dye to reach the main river channel from the point of injection. In dye run No. 2, it was estimated that less than two minutes was required for the injected dye to reach the main channel from the No. 3 sewage treatment plant effluent line. In dye runs Nos. 3 and 4, the 40% rhodamine B dye

TABLE VI

SUMMARY OF TIME-OF-TRAVEL STUDIES CARRIED OUT IN THE
NORTH SASKATCHEWAN RIVER

(During January and February - 1970)

From	To	Center- line Dis. Miles	Peak- Peak Time Hrs.	Av. Vel. MPH	Av. Vel. fps	Mean Vel. fps	Approx. Dis. cfs
*#3 STP	Low Level Br.	1.10	1.10	1.00	1.47	1.40	2520
*Low Level Br.	Capilano Br.	3.26	3.73	0.87	1.28		2520
*Capilano Br.	Clover Bar Br.	4.28	4.30	0.99	1.46		2520
Clover Bar Br.	Sherritt Gordon	18.0	21.40	0.84	1.23	1.23	2520
Sherritt Gordon	Vinca Monitoring	11.8	14.18	0.83	1.22	1.19	2390
Vinca Monitoring	Waskatenau Br.	19.8	24.83	0.79	1.16		2390
Hopkins Fy.	Elk Point Br.	6.1	6.67	0.91	1.34	1.34	2930
Elk Point Br.	Heinsberg Br.	20.5	21.32	0.96	1.41		2930
Heinsberg Br.	Lea Park Br.	11.5	13.40	0.86	1.26		2930
Lea Park Br.	Lloyd. Fy.	19.4	21.15	0.92	1.34		2930

*Open Water Conditions.

solution was introduced directly through the ice into the main channel stream. This provided an instantaneous injection of the dye solution.

3. Velocity in Open Water

Steady, uniform flow conditions were assumed throughout the entire study area from Edmonton to Battleford, Sask. In estimating the travel time for various discharges in the open water reach between the Low Level Bridge and the City of Edmonton Lagoons, the velocity-discharge relationship (FIGURE 22) for the gauging station at the Low Level Bridge was utilized. FIGURE 22 was derived from the stage-discharge curve (FIGURE 19) and the stage-velocity curve (FIGURE 20).

In an attempt to establish the credibility of FIGURE 22, time-of-travel run No. 2 was undertaken. The discharge, as determined from the Low Level recording gauge when the dye cloud passed by, was 2520 cfs and the mean velocity was 1.47 fps (TABLE VI). For a discharge of 2520 cfs, the measured mean velocity of 1.47 fps agreed with the velocity shown in FIGURE 22.

FIGURE 22 was used to estimate the open water travel time corresponding to the discharges encountered during the DO-BOD sampling runs. The velocity which corresponded to the discharge measured at the start of each sampling run was used throughout the reach of open water.

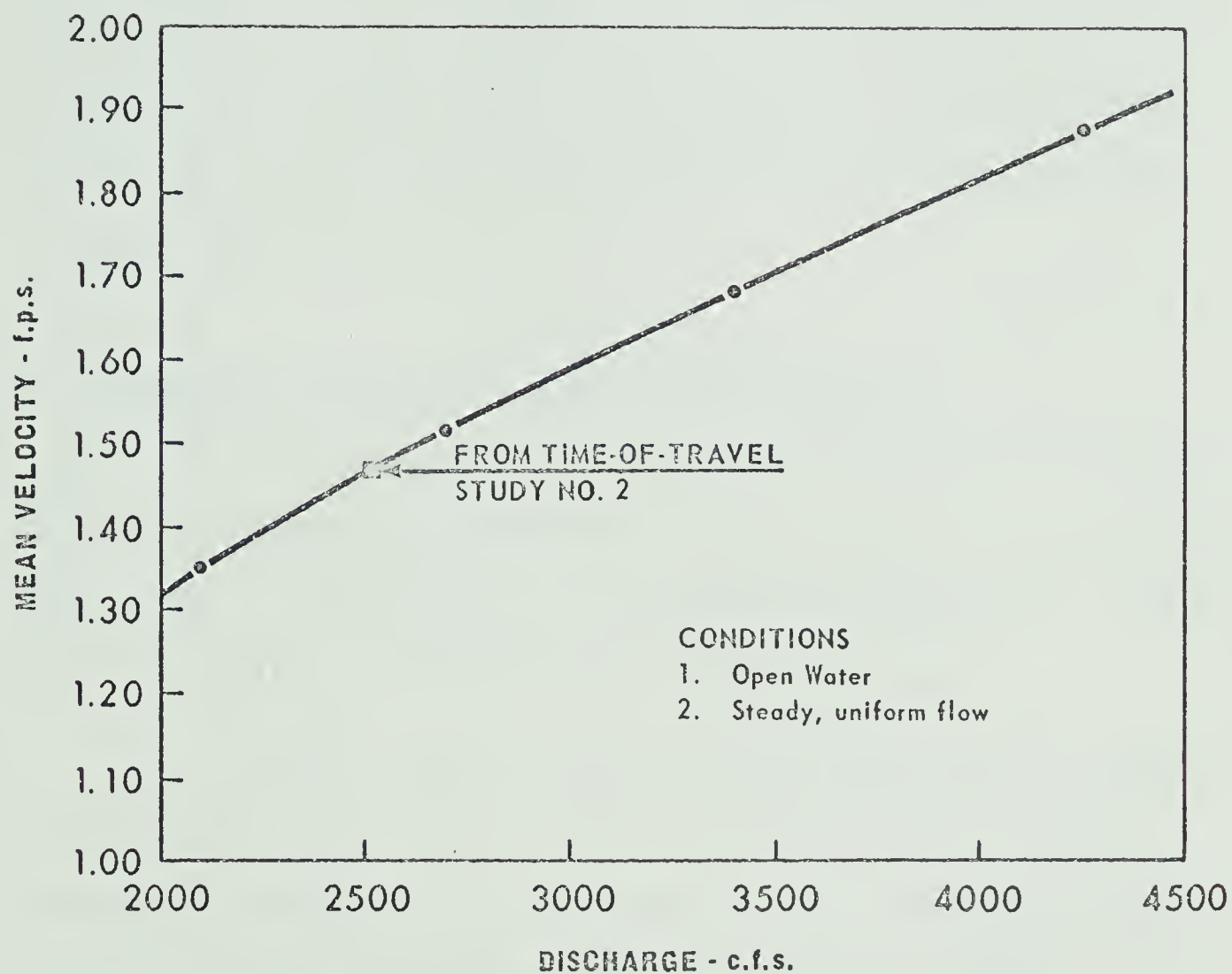


FIGURE 22: VELOCITY-DISCHARGE CURVE FOR NORTH SASKATCHEWAN RIVER AT LOW LEVEL BRIDGE EDMONTON (compiled from Fig. 19 and 20)

4. Velocity Under Ice-Cover Conditions

The results of the time-of-travel studies carried out under ice-cover conditions are summarized in TABLE VI. The averaged velocity and the corresponding discharge were plotted to obtain a velocity-discharge relationship curve (FIGURE 23). This curve was used to estimate the travel time corresponding to the discharge occurring at the time of any given DO-BOD sampling run under conditions of ice-cover.

5. Velocity-Discharge Relationship Summary

The interpolation and presentation of the time-of-travel results, as outlined in the previous paragraphs, were used to simplify the prediction of reasonable travel times required for each DO-BOD sampling run.

Caution must be exercised in the use of FIGURE 23 as it is only based on four time-of-travel studies. Usage of FIGURES 22 and 23 imply steady, uniform flow conditions, which are rarely found in natural streams. The assumption of steady, uniform flow may be rationalized, in part, because river discharges during any given day remained fairly constant and the measured velocities in the time-of-travel studies were in close agreement. Also, throughout the field investigations, ice thickness measurements remained constant at any given location and water filled all augered ice holes to the surface. This would

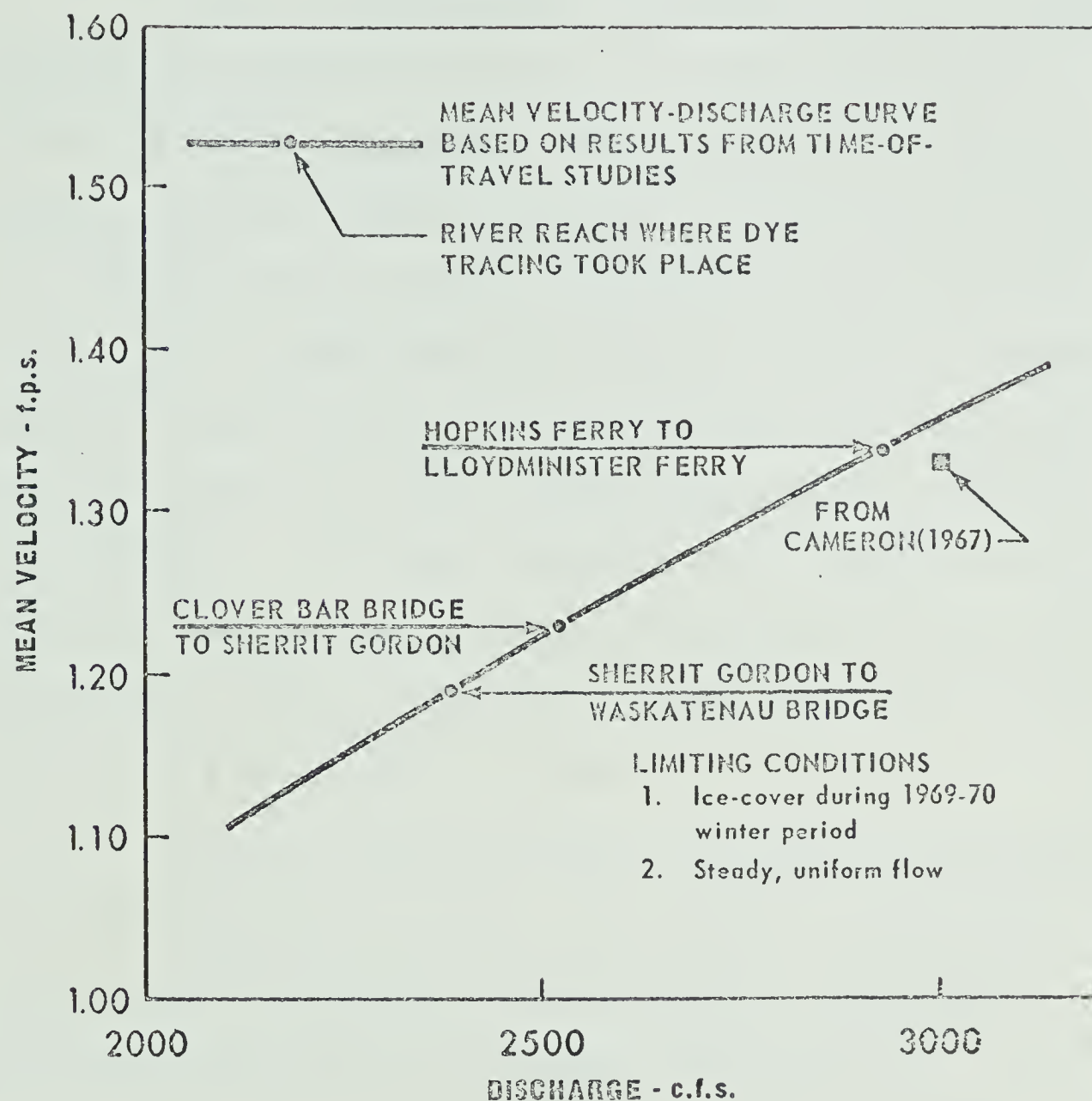


FIGURE 23: VELOCITY-DISCHARGE CURVE FOR NORTH SASKATCHEWAN RIVER - EDMONTON TO LLOYDMINISTER FERRY.

seem to imply that the river, under ice cover, flowed under pressure and the cross-sectional area of flow remained fairly constant.

Due to the possible differences in ice formation conditions from year to year, the relationship shown in FIGURE 23 may be applicable only to the 1969-70 winter period. Cameron (1967) conducted a time-of-travel study in a reach under ice cover from Myrnam to Lloydminster Ferry. For an approximate discharge of 3000 cfs, Cameron measured a mean velocity of 1.33 fps and this velocity was very close to a mean velocity of 1.36 fps as taken from FIGURE 23. This may imply that if a series of time-of-travel studies was conducted over several winter periods, an accurate velocity-discharge relationship for all ice-cover conditions could be found.

Despite the previously discussed shortcomings, the method employed in this study offers a practical solution to the problem of ascertaining reasonably accurate travel times for DO-BOD sampling runs.

CHAPTER VI

DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND ANALYSIS

1. Introduction

In the prediction of the rates of deoxygenation, reaeration and BOD removal in natural polluted streams, comprehensive sampling programs encompassing different discharges, flow velocities, and waste loadings are required. Due to the short period of favourable ice conditions, the DO-BOD sampling program for this study was restricted to four separate runs. The results obtained from these sampling runs are not conclusive but give, at best, a reasonable estimate of the rates of DO utilization and BOD removal known to exist in the North Saskatchewan River under ice-cover conditions.

Based on the discharge at the commencement of each DO-BOD sampling run, as determined from the Low Level Bridge gauging station, the travel time of the sampled slug of water between successive downstream locations was determined. The velocities determined from FIGURES 22 and 23 were assumed to remain constant throughout both the open water and ice-covered reaches as was shown to be the case by the dye tests discussed in Chapter V. A summary of the travel times used for each of the four DO-BOD sampling runs is shown in TABLE VII.

TABLE VII

SAMPLING RUN TRAVEL TIMES

Sampling Sites		Sampling Run No. 1			Sampling Run No. 2			Sampling Run No. 3			Sampling Run No. 4		
		From	To	Dist. Miles	Accum. Dist. Miles	Travel Time Hours	Travel Time Days	Accum. Travel Time Days	Travel Time Hours	Travel Time Days	Accum. Travel Time Days	Travel Time Hours	Travel Time Days
*Low Level	Clover Bar			7.5	7.5	3.09	0.34	0.34	7.50	0.31	0.31	7.85	0.33
*Clover Bar	Lagoons			7.3	14.8	7.87	0.33	0.67	7.30	0.30	0.61	7.64	0.32
Lagoons	Ft. Sask.			8.4	23.2	11.10	0.46	1.13	9.88	0.41	1.02	10.63	0.44
Ft. Sask.	Vinca Monit. Sta.			15.2	38.2	20.08	0.84	1.97	17.38	0.74	1.76	19.24	0.80
Vinca Monit. Sta.	Waskatenau			19.8	58.2	26.16	1.09	3.06	23.29	0.97	2.73	25.06	1.04
Waskatenau	Pakan			17.2	75.4	22.72	0.95	4.01	20.23	0.84	3.57	21.77	0.91
Pakan	Shandro			16.3	91.7	21.53	0.90	4.91	19.18	0.80	4.37	20.63	0.86
Shandro	Duverney			30.8	122.6	40.82	1.70	6.61	36.35	1.51	5.88	39.11	1.63
Duverney	Myrnam			21.8	144.4	28.80	1.20	7.81	25.65	1.07	6.95	27.59	1.15
Myrnam	Hopkins			9.6	154.0	12.68	0.53	8.34	11.29	0.47	7.42	12.15	0.51
Hopkins	Elk Point			6.1	160.1	8.06	0.34	8.68	7.18	0.30	7.72	7.72	0.32
Elk Point	Lindberg			12.2	172.3	16.12	0.67	9.35	14.35	0.60	8.32	15.44	0.64
Lindberg	Heinsberg			8.3	180.6	10.96	0.46	9.81	9.76	0.41	8.73	10.51	0.44
Heinsberg	Lea Park			11.5	192.1	15.19	0.63	10.44	13.53	0.56	9.29	14.56	0.61
Lea Park	Lloyd. Ferry			19.4	211.5	25.63	1.07	11.51	22.82	0.95	10.24	24.56	1.02
Lloyd. Ferry	North Battleford			116.5	328.0	153.90	6.41	17.92	137.06	5.71	15.95	147.47	6.14
												107.87	4.49

Q = 2120 cfs
V(Open Water) = 1.36 fps
V(Under Ice) = 1.11 fps

Q = 2540 cfs
V(Open) = 1.47 fps
V(Ice) = 1.24 fps

Q = 2280 cfs
V(Open) = 1.40 fps
V(Ice) = 1.16 fps

Q = 3930 cfs
V(Open) = 1.81 fps
V(Ice) = 1.58 fps

*Open Water Conditions

Due to a delay in receiving the shipment of 40 per cent rhodamine B dye solution, the first two DO-BOD sampling runs were carried out using the fluorescein time-of-travel study results. These sampling runs were carried out at discharges very close to the discharges of the fluorescein dye tracing tests (2100-2500 cfs). Subsequently the travel times used were unaltered by the rhodamine B dye tracing test results, which were carried out at a higher discharge (2930 cfs).

As outlined in Chapter IV, each sampling run consisted of determining the river DO and BOD-5-20 at successive downstream locations. A complete summary of the field observations, as well as those obtained by the Alberta Division of Environmental Health Services during the field investigation period, is shown in Appendix D (FIGURE D1). The data in FIGURE D1 is arranged so that the measured DO value is shown above the BOD value and these are plotted with respect to the date and location of each sample taken. The results of the four DO-BOD sampling runs, taken from FIGURE D1, are shown on FIGURES 24 and 25.

2. Waste Loadings in the North Saskatchewan River

In studies of this nature, it is imperative that the BOD sample taken at any given location be representative of the actual BOD loading in the river at the time of sampling. This is particularly important at locations

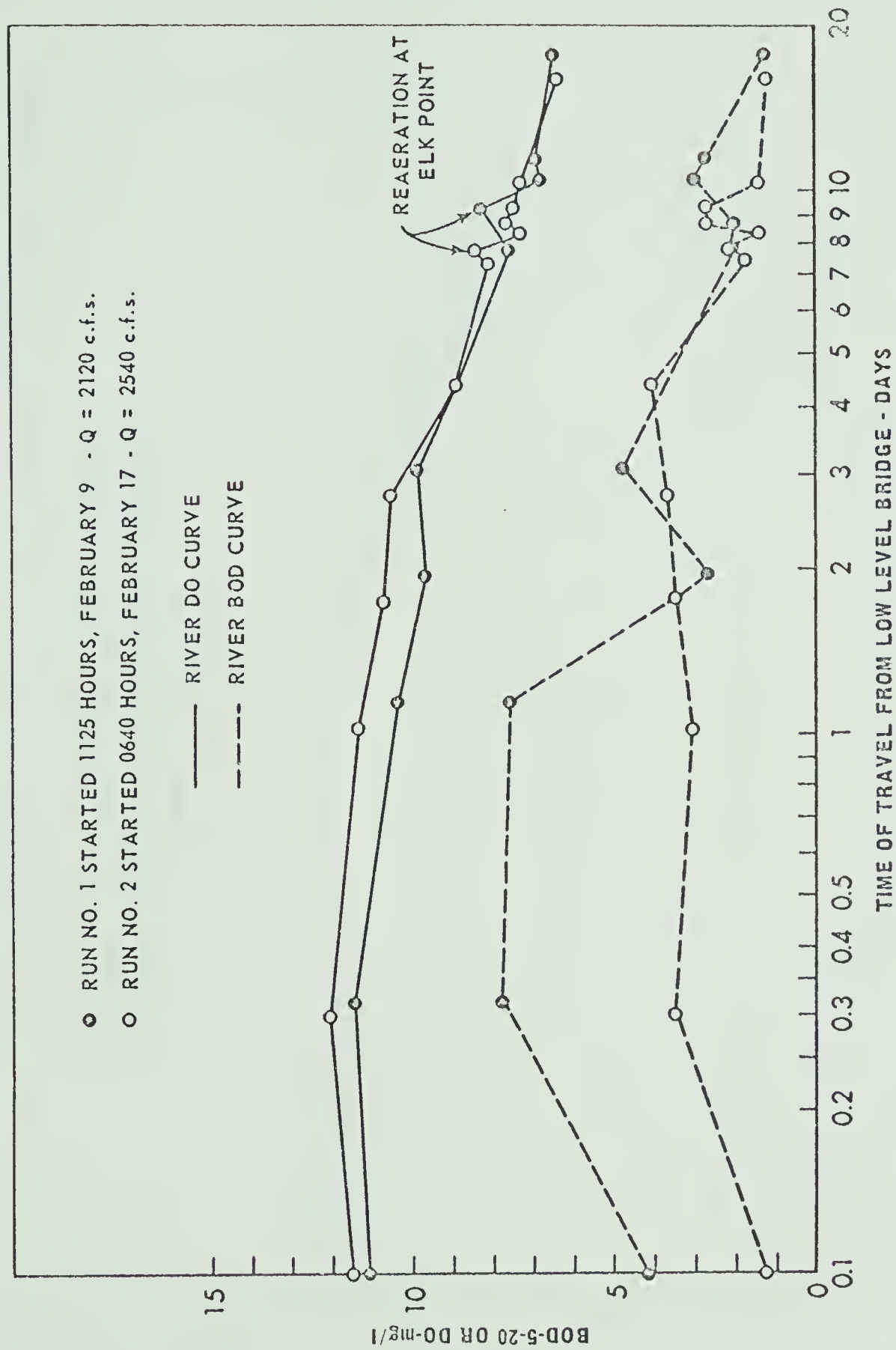


FIGURE 24: DO - BOD CURVES FOR NORTH SASKATCHEWAN RIVER - FEBRUARY 1970

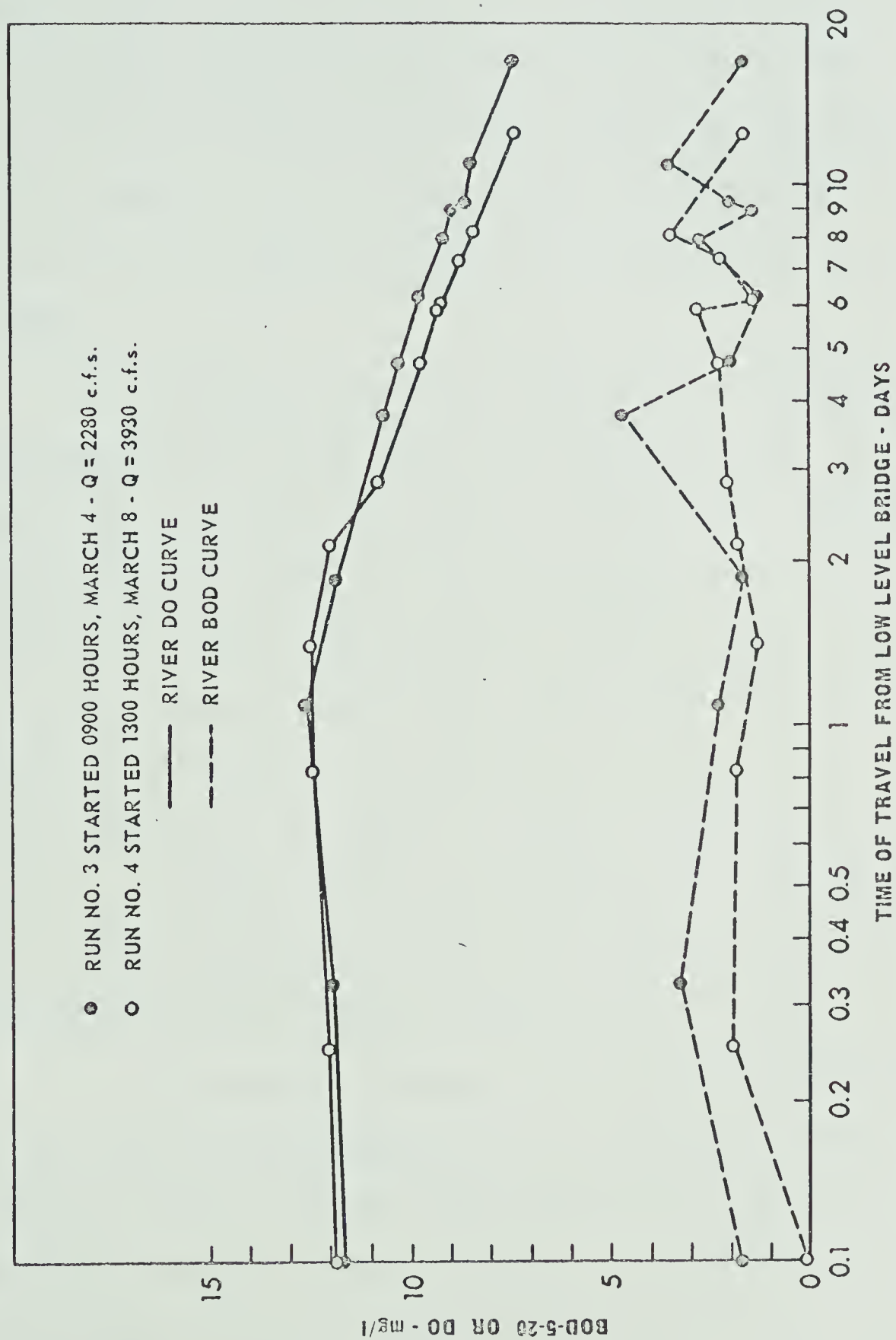


FIGURE 25: DO - BOD CURVES FOR NORTH SASKATCHEWAN RIVER - MARCH 1970

immediately downstream from sources of pollution. Depending on the hydraulic features of the stream, a considerable distance may be required for the stream to disperse and mix a concentrated mass of pollutant introduced to the stream. Unless this pollutant is properly dispersed and mixed, samples taken in this reach of dilution and longitudinal mixing will not truly represent the BOD loading in the stream.

For this study, the longitudinal dispersion characteristics of the North Saskatchewan River in both open water and under ice-cover conditions are unknown. Because of the length of river required to properly disperse and mix the pollutants, the BOD results obtained at a few locations immediately downstream from sources of pollution are subject to misinterpretation. This particularly applies to the samples taken at the Low Level Bridge, located 1.1 miles downstream from the No. 3 Sewage Treatment Plant, and at the Clover Bar Bridge, located 3.3 miles downstream from the Main Sewage Treatment Plant.

As stated in Chapter II, the major BOD Loading to the North Saskatchewan River in Alberta is caused by domestic sewage effluent from the City of Edmonton No. 3 and Main Sewage Treatment Plants. A comparison of the City of Edmonton Sewage Treatment Plant BOD loading to the total BOD loading in the river on certain days is shown in

TABLE VIII. The total BOD loading is determined from samples taken of all effluents discharged to the North Saskatchewan River in Alberta on a given day. Based on only four days data, it can be seen from TABLE VIII that the two sewage treatment plants can contribute between 41 and 79 percent of the total BOD loading in the North Saskatchewan River on any given day.

On the date of each sampling run, the daily BOD loading from the No. 3 and Main Sewage Treatment Plants was compared to the BOD measured at the Clover Bar Bridge. The results of this survey are summarized in TABLE IX. The presentation of TABLE IX is subject to error in that the Clover Bar BOD measurements are based on grab samples taken at only one particular time during a given day; while the BOD loadings from the plants to the river are based on 24 hour composite samples. For more meaningful results, composite samples should have been taken at the Clover Bar Bridge instead of grab samples. The percent contribution by the sewage treatment plants was based on the comparison of the total plant loading to the river with that measured at the Clover Bar Bridge.

The BOD of samples taken across the river section at the Clover Bar Bridge was found to vary by up to fifty per cent, thus indicating incomplete mixing at that location. During the DO-BOD sampling runs, BOD samples at the Clover Bar Bridge were taken from the main stream, where the highest readings were found. These higher,

TABLE VIII

BOD LOADINGS IN THE NORTH SASKATCHEWAN RIVER
(Based on Effluent Tests)

	Nov. 25 1969	Jan. 6 1970	Feb. 2 1970	Mar. 17 1970
(a) Total BOD Loading in River - lbs/day	32,677	29,910	33,650	26,665
(b) BOD Loading in River Due to Main and No. 3 STP Effluents lbs/day	20,674	12,230	26,414	13,237
Per cent Contri- bution from STP Effluents	63.4	40.9	78.4	49.6

(a) Data from Alberta Division of Environmental Health Services

(b) Data from City of Edmonton Engineering Department

TABLE IX

BOD LOADINGS IN THE NORTH SASKATCHEWAN RIVER
AT EDMONTON

	Feb. 9 1970	Feb. 17 1970	Mar. 4 1970	Mar. 8 1970
Mean Daily Flow cfs	2,260	2,630	2,570	3,340
BOD Measured at the Clover Bar Bridge - mg/l	7.7 ^(a)	3.4	3.3	2.0
(b) BOD Loading in River due to No. 3 and Main STP's - mg/l	1.7	2.1	1.3	0.6
Per cent BOD Loading in River Due to No. 3 and Main STP's.	22.1	61.8	39.4	30.0

(a) High BOD at Clover Bar Bridge due to an initial BOD of 4.0 mg/l upstream from Edmonton.

(b) Data supplied by City of Edmonton Engineering Department.

unrepresentative samples probably account for the lower per cent contribution range (22 - 62 per cent) found in TABLE IX, when compared to the range in TABLE VIII (40 - 78 per cent).

3. Reaeration in the North Saskatchewan River

During the period of field investigation, the North Saskatchewan River, prior to receiving waste effluents from the Edmonton area, was found to have a DO deficit ranging from 2.0 to 2.5 mg/l (81 to 84 per cent saturation). In the open water reach downstream from the City of Edmonton Power Plant (FIGURE 7), reaeration reduced this deficit to a point where, at the Clover Bar Bridge, the deficit was found to vary from 1.3 to 1.9 mg/l (86 - 91 per cent saturation) during the month of February (FIGURE 24). In March, when the open water reach extended well past the City of Edmonton Lagoons, the DO deficit was reduced up to the Fort Saskatchewan Bridge (FIGURE 25). The deficit at this point varied from 1.1 to 1.4 mg/l (90 to 92 per cent saturation).

The rate of reaeration that takes place in a stream is proportional to the dissolved oxygen deficit and is generally expressed as:

$$\frac{dD}{dt} = -K_2 D \quad (5)$$

where D is the dissolved oxygen deficit and K_2 is the reaeration coefficient. An attempt was made to determine the reaeration coefficient based on field data, between the Low Level and Clover Bar Bridges and to compare this coefficient with a theoretical coefficient determined from a general relationship given by Eckenfelder and O'Connor (1961).

In determining the reaeration coefficient from field data, the results from DO-BOD sampling runs Nos. 2 and 3 were used. The calculations are tabulated in TABLE X.

A general approximate formula for the reaeration coefficient of natural rivers, as given by Eckenfelder and O'Connor (1961), is expressed as:

$$K_2 = \frac{(D_L U)^{1/2}}{H^{3/2}} \quad (6)$$

where K_2 is the reaeration coefficient (base e), D_L is the diffusibility of oxygen in water and is equal to $0.000081 \text{ ft}^2/\text{hr}$ at 20°C , U is the velocity of flow and H is the depth of flow. The effect of temperature on the reaeration coefficient is given as:

$$K_T = K_{20} \times 1.047^{T-20} \quad (7)$$

where K_T is the reaeration coefficient at temperature $T^\circ\text{C}$, and K_{20} is the reaeration coefficient calculated from equation 6.

TABLE X

CALCULATION OF REAERATION COEFFICIENT
FOR NORTH SASKATCHEWAN RIVER AT EDMONTON
FEBRUARY AND MARCH, 1970

Run	Location	Travel Time Days	D0 Deficit mg/l	Difference In D0 Deficit Log (Base 10)	Reaeration Coefficient (K ₂)(Base 10) Per Day
1	Low Level Br.	0	1.5		
	Clover Bar Br.	0.31	1.3	0.0622	0.201
2.	Low Level Br.	0	1.4		
	Clover Bar Br.	0.34	1.2	0.0669	0.197

Assuming a discharge of 2410 cfs (the average discharge of DO-BOD sampling runs Nos. 2 and 3), the velocity of flow would be 1.44 fps (FIGURE 22) and the average depth of flow would be 3.26 feet (FIGURE 19). Substituting in equation 6, K_2 (base e) at 20°C will be:

$$K_2 = \frac{(0.000081 \times 1.44 \times 3600)^{1/2} \times 24}{(3.26)^{3/2}} = 1.463$$

Substituting $K_{20} = 1.463$ into equation 7, K_2 at 1°C (the average temperature of the open water reach) will be:

$$\begin{aligned} K_2 \text{ (at } 1^\circ\text{C)} &= 1.463 \times 1.047^{-19} = 0.584 \text{ (Base e)} \\ &= 0.254 \text{ (Base 10)} \end{aligned}$$

The calculated results (TABLE X), although based on only two runs, are very close to the theoretical coefficient. Further sampling runs in the open water reach are required if a reasonably accurate reaeration coefficient is to be determined.

In the fall of 1970, the Clover Bar Power Plant is expected to begin power generation. This plant, located approximately two miles downstream from the Clover Bar Bridge (FIGURE 8), will be discharging cooling water effluent which will, during the winter months, keep the river ice-free up to and probably past the Fort Saskatchewan Bridge. Additional reaeration and an increase in biological activity may be expected to occur downstream from the plant.

4. Deoxygenation in the North Saskatchewan River

In carrying out the four sampling runs, as outlined in Chapter IV, river DO concentrations were measured at all sampling locations. These were determined in the field by the Modified Winkler Method (Standard Methods, 1965). The results of the DO determinations are graphically summarized in Appendix D (FIGURE D1) and are shown in FIGURES 24 and 25.

During periods of ice-cover conditions, deoxygenation in the river downstream from Edmonton commences one to two days travel time from the Low Level Bridge (FIGURES 24 and 25). With the commencement of deoxygenation, the DO levels in the river decrease at a fairly uniform rate downstream to Battleford, Saskatchewan. The effect of slight reaeration due to open water upstream from the Elk Point Bridge and downstream from Lindberg (7-9 days travel time from the Low Level Bridge), is illustrated in FIGURES 24 and 25.

As discussed in Appendix A, the formulation of deoxygenation and reoxygenation in polluted natural waters is generally based on the rate of change in DO deficit at any given time. For the purpose of this study, it is felt that DO utilization, which may be defined as the total amount of DO used to oxidize organic wastes within a given reach of river, is more meaningful than using

D0 deficit. Since a D0 deficit already existed upstream from Edmonton, and since reaeration takes place in the open water reach, the D0 deficit at locations downstream from Edmonton does not give a direct measure of the amount of D0 required to oxidize the organic wastes discharged into the river within the study area.

The dissolved oxygen concentration in the river at the Low Level Bridge, which was used as a starting point for the D0-BOD sampling runs, was considered to be representative of the initial D0 concentration in the river upstream from Edmonton. This assumption is reasonable in that testing carried out on the river (under ice-cover) two miles upstream from the Low Level Bridge showed that the D0 concentration at the Low Level Bridge was only 0.1 to 0.2 mg/l higher than the D0 concentration two miles upstream. The slight increase is due to the open water conditions commencing one mile upstream from the Low Level Bridge (FIGURE 7). The D0 utilized at each sampling location was determined by subtracting the measured D0 from the initial D0 concentration at the Low Level Bridge. The BOD-D0 utilization results obtained from each sampling run are shown in FIGURES D2 to D5 and are combined in FIGURE D6 (Appendix D).

From FIGURES D3 to D5, it can be seen that possibly three different rates of deoxygenation occur between Vinca and Battleford in the North Saskatchewan River under ice-

cover conditions. The highest rate of deoxygenation occurs approximately between Vinca and Duvernay, while the rate of deoxygenation between Duvernay and Lloydminster Ferry is approximately one-third the higher upstream rate. The rate between Lloydminster Ferry and Battleford appears to be approximately one-third the rate of deoxygenation from Duvernay to Lloydminster. The rates of deoxygenation determined from sampling runs Nos. 2 and 3 (discharge of 2540 and 2280 cfs respectively) are very similar (FIGURES D3 and D4). The three rates of deoxygenation for the higher discharge of 3930 cfs (FIGURE D5) are approximately 44 per cent higher than the rates of deoxygenation for the lower discharges. Due to insufficient sampling data from DO-BOD sampling run No. 1, the rates of deoxygenation at 2180 cfs could not be determined. (FIGURE D2). The rates of deoxygenation, as determined from FIGURES D3 to D5, are summarized in TABLE XI.

An attempt was made to derive formulas which would be of use in predicting the amount of dissolved oxygen that would be utilized downstream from Edmonton (under ice-cover conditions). When the DO utilization and corresponding travel time data is plotted on a semi-log plot (FIGURE D7), a fairly straight line relationship is discernible downstream from the Vinca monitoring station (approximately two days travel time from the Low Level Bridge). The slope (K) of the best fit (by eye) straight line for the sampl-

TABLE XI

APPROXIMATE RATES (K_d) OF DEOXYGENATION IN THE
NORTH SASKATCHEWAN RIVER UNDER ICE-COVER

	Run No. 2	Run No. 3	Run No. 4
Discharge - cfs	2540	2280	3930
Deoxygenation Rate (Base 10 Log)/day			
Vinca to Duverney	0.094*	0.092	0.165
Duverney to Lloyd- minister Ferry	0.033	0.034	0.059
Lloydminister Ferry to Battleford, Sask.	0.013	0.019	0.024

*Estimated

ing runs was determined and is shown in FIGURE D7. The equation for the semi-log straight line relationship in FIGURE D7 may be written as:

$$D_2 = D_1 + S \text{ LOG } \frac{T_2}{T_1} \quad (8)$$

where D_2 is the DO utilized (mg/l) downstream from Vinca at time T_2 (days) below the Low Level Bridge, D_1 is the DO utilized (mg/l) at Vinca at time T_1 (days) and S is a coefficient (mg/l) indicated by the slope of the straight line in FIGURE D7. Using the value of $S = 4.43$ (FIGURE D7), equation 8 may be rewritten as:

$$D_2 = (DO_V - DO_L) + 4.43 \text{ LOG } T_2 - 4.43 \text{ LOG } T_1 \quad (9)$$

where the term $DO_V - DO_L$ represents the difference in the river DO concentration at Vinca and the Low Level Bridge in time T_1 days from the Low Level Bridge.

For each DO-BOD sampling run, the measured DO utilized at Vinca, as well as the travel time to Vinca was substituted in equation 9 and plotted as a dotted line in FIGURES D8 and D9. From these plots it can be seen that the DO utilized downstream from Vinca, as determined from equation 9, would give a reasonable estimate of the actual DO utilized in the field (within 15 per cent).

Using an approximate discharge of 2930 cfs, Cameron (1967) determined mean DO utilization values at various locations downstream from Vinca for the 1966-67

winter period. The mean values and the corresponding travel times determined from FIGURES 22 and 23 (for 2930 cfs) are plotted in FIGURE D10. Also shown as a dotted line is equation 9 containing the mean D0 utilized at Vinca (2.4 mg/l) and the travel time from the Low Level Bridge to Vinca (1.65 days). Equation 9, when plotted in FIGURE D10, shows very close agreement with the average values determined by Cameron.

From samples taken during the 1966-67 winter period, Cameron (1967) determined a S value of 3.52 instead of a value of 4.43 as determined in this study. Cameron calculated the slope value of 3.52 by using the average D0 utilization value of samples taken at Vinca and Elk Point Bridge. As previously discussed and from FIGURE 24, it can be seen that the river D0 concentration at the Elk Point Bridge is generally higher than the normal D0 concentration upstream and downstream from the Elk Point Bridge. Because of the slight river reaeration upstream from the bridge, it is felt that the D0 utilization value at Elk Point is not quite representative of the normal trend of D0 utilization under ice cover in the North Saskatchewan River (FIGURE D8). Usage of field data from the Elk Point Bridge location in equation 8 will give a S value that is lower than the value that is considered to be representative of the river. To illustrate, the data from D0-BOD sampling run No. 2 (at 2540 cfs) may be considered representative of

the data obtained by Cameron (1967) at an approximate discharge of 3000 cfs. Substituting the D0 utilized at Vinca and Elk Point (0.8 and 3.1 mg/l respectively) and the travel times (1.76 and 7.72 days respectively) from run No. 2 into equation 8:

$$3.1 = 0.8 + S \text{ LOG } \frac{7.72}{1.76}$$

$$S = \frac{2.3}{0.642} = 3.58 \text{ per day.}$$

This S value is very close to the S value of 3.52 determined by Cameron (1967).

Based on the number of samples taken in this study at various locations throughout the study area between Edmonton and Battleford, and based on the presentation of this data in FIGURES D7 to D9, it is felt that the value of 4.43 is a reasonable estimate of the S factor in equations 8 and 9. It must be realized that equation 9 is valid for the D0-BOD conditions found during this study program. The fact that the equation showed close agreement with the average values determined by Cameron (1967) does not suggest that the formula may be applicable to the all winter periods.

It is felt that the slope (S) value is dependent not only on BOD loadings in the river but also may be influenced by discharge. The relationship of these factors to the slope (S) value requires further study.

5. BOD Reduction in the North Saskatchewan River

The ideal situation for predicting BOD removal rates would be to determine the BOD at various locations downstream from a single source or several sources of waste effluents discharged within a single given short reach of river. Throughout the study area from Edmonton to Battleford, the North Saskatchewan River receives waste loadings from several locations (TABLE II). These various sources of waste effluents discharged to the river cause variable rates of BOD reduction within the study course, thus preventing the determination of an overall BOD removal rate that may be applicable between Edmonton and Battleford.

The BOD-5-20 data obtained from the four sampling runs is shown in FIGURES D2 to D5 and summarized in FIGURE D6. It is felt that the data presented in FIGURES D2 to D6 is insufficient to provide an accurate BOD removal rate (or rates), however, certain rate trends in certain given reaches between Vinca and Battleford may be derived from these plots. The effect of waste effluents on the BOD loading in the river is readily discernible in FIGURES D2 to D6. A rapid rise in BOD-5-20 downstream from sources of waste effluents being discharged to the river at Edmonton, Fort Saskatchewan, Duvernay and Lindberg is evident. A rapid decrease in BOD occurs approximately one to two days downstream from these sources of pollution.

Between Edmonton and Lloydminster Ferry, the rate of BOD reduction appears to be greater than the rate of deoxygenation. Between Lloydminster Ferry and Battleford, the rate of BOD removal appears to be the same as the rate of deoxygenation.

From FIGURES 24 and 25, it can be seen that the DO utilized within the study area (between Edmonton and Battleford) was 4.3 to 5.0 mg/l, while the total BOD removed varied 0.6 to 1.9 mg/l. Some possible explanations for the difference between the DO used and the BOD removed are:

1. Due to the differences in the biochemical and physical characteristics of each environment, there is an obvious error in comparing BOD-5-20 bottle tests incubated in the laboratory with that of the BOD in the river at 0°C.
2. Under conditions of winter flows and BOD loadings very similar to those of this study, Cameron (1967) found an approximate drop in BOD of 75 per cent between the lagoons and Fort Saskatchewan. Since winter conditions during this study program precluded any sampling at the lagoon site, the actual drop in BOD from the lagoons to the Fort Saskatchewan Bridge could not be determined. However, using Cameron's reduction rate of 75 per cent, the total BOD removed in this study would then be between 2.4 to 7.6 mg/l.

3. The extra DO utilized may be taken up by oxygen demanding material on the rocks and bed of the river downstream from Vinca. Samples of BOD taken in the river will not include the bottom oxygen demand.

The rates of BOD removal (K_r) were calculated for the reaches showing definite trends of BOD reduction (FIGURES D2 to D5). These calculations are summarized in TABLE XII.

Based on data from the four DO-BOD sampling runs and the presentation of this data in FIGURES D2 to D6, it is evident that BOD removal in the North Saskatchewan River under ice cover is influenced by factors other than that of direct oxidation of organic matter in the water phase. Because the rate of BOD removal is generally higher than the rate of deoxygenation, it is postulated that sedimentation and adsorption to the river bottom play a major role in removing BOD from the River between Edmonton and Lloydminster Ferry. Based on only two runs, it appears that BOD may be removed only by oxidation between Lloydminster Ferry and Battleford.

TABLE XII

APPROXIMATE BOD REMOVAL RATES (K_r) FOR VARIOUS REACHES
UNDER ICE COVER IN THE NORTH SASKATCHEWAN RIVER

	Run No. 1	Run No. 2	Run No. 3	Run No. 4
Ft. Sask. to Vinca Br. Monitoring Site				
BOD Reduction - Log (Base 10)	0.241	-	0.131	0.165
Travel Time - Days	0.84	-	0.81	0.59
BOD Removal Rate - Per Day	0.29	-	0.16	0.28
Hopkins Ferry to Lindberg				
BOD Reduction - Log (Base 10)	-	0.091	0.301	0.349
Travel Time - Days	-	0.90	0.96	0.71
BOD Removal Rate - Per Day	-	0.10	0.31	0.49
Lloydminster Ferry to Battleford, Sask.				
BOD Reduction - Log (Base 10)	-	0.053	-	0.314
Travel Time - Days	-	5.71	-	4.49
BOD Removal Rate - Per Day	-	0.01	-	0.07

CHAPTER VII

SUMMARY AND CONCLUSIONS

1. Time-of Travel Measurements

Four time-of-travel studies were successfully carried out using 25 per cent fluorescein and 40 per cent rhodamine dye solutions as soluble fluorescent contaminants in each of two studies. With proper fluorometer filter selection and calibration, both dyes can be readily detected at concentrations as low as 0.5 ppb. The high photochemical decay rate of fluorescein restricts its usage in time-of-travel measurements to conditions of darkness or ice cover. The cost of the rhodamine B (per pound of solution) is approximately twice the cost of an equivalent pound of fluorescein dye solution.

Values of mean velocity (peak-to-peak) measured in the North Saskatchewan under ice cover varied from 1.19 to 1.34 fps for discharges of 2390 and 2930 cfs respectively (TABLE VI). Travel times for the DO-BOD sampling runs were based on a plot of the mean velocities determined from the time-of-travel studies (FIGURES 22 and 23). For the purposes of this study, the establishment of suitable travel times was based on the assumption of steady, uniform flow throughout the study area. It was further assumed that the velocity of flow in open water, as well as the velocity of flow

under ice-cover conditions remained constant for a given discharge throughout the respective reaches.

2. BOD-5-20 Loadings to the River

Based on data supplied by the Alberta Division of Environmental Health Services and the City of Edmonton Engineering Department, between 40 to 80 per cent of the total daily BOD loading in the North Saskatchewan River (in Alberta) during the winter months is derived from the Main and No. 3 Sewage Treatment Plants in Edmonton.

3. Reaeration in the River

Downstream from the 105th Street Bridge in Edmonton, a stretch of the North Saskatchewan River is kept open during the winter months by cooling water effluent from the City of Edmonton Power Plant. This effluent, combined with warmer than normal air temperatures maintained the open water reach up to 16 miles during most of this study. Based on two sampling runs, the reaeration coefficient (K_2) in this open stretch was computed to be 0.20 per day (base 10). This reaeration coefficient showed very close agreement with the theoretical reaeration coefficient of 0.254 per day (base 10) determined from a general equation proposed by Eckenfelder and O'Connor (1961).

4. Deoxygenation and BOD Removal in the North Saskatchewan River

Deoxygenation in the study area commences one to two days travel time from the Low Level Bridge in Edmonton. The rate of deoxygenation (K_d) was found to vary between Vinca and Battleford. Between Vinca and Duvernay, K_d varied from 0.09 to 0.16 per day; between Duvernay and Lloydminster Ferry, K_d varied from 0.03 to 0.06; and from Lloydminster Ferry to Battleford, the rate of deoxygenation (K_d) varied from 0.01 to 0.02 per day. All rates are base 10 log. These rates of deoxygenation are essentially the same rates of deoxygenation found by Briggs (1966) for BOD bottle tests at 0°C and are indicative of the rate of deoxygenation of organic matter in the water phase at 0°C.

The rates of BOD removal, as estimated for several reaches within the study area, varied from 0.10 to 0.49 per day (base 10) between Fort Saskatchewan and Lloydminster Ferry; while between Lloydminster Ferry and Battleford, the rate of BOD removal varied from 0.01 to 0.07 per day.

From the foregoing discussion and FIGURES D2 to D10, the following is postulated for the North Saskatchewan River under ice-cover conditions between Edmonton and Battleford:

1. Reaeration of the river takes place within the first day of travel from the Low Level Bridge. Between one to two days travel time from the Low Level Bridge, the effect of oxygen demanding materials in suspension begin to show as the dissolved oxygen levels become lower in the river.
2. Between Edmonton and Lloydminster Ferry, much of the oxygen demanding material from waste effluents discharged to the river is removed by sedimentation and adsorption to the rocks and bed of the river. This is indicated by the rapid use of BOD in certain reaches of the river.
3. Based on data obtained in the study program, the DO that will be used in the river at any location downstream from Vinca may be estimated from:

$$D_2 = (DO_V - DO_L) + 4.43 \log T_2 - 4.43 \log T_1 \quad (9)$$

where D_2 is the DO utilized (mg/l) downstream from Vinca at time (T_2) days from the Low Level Bridge, and $DO_V - DO_L$ represents the difference in river DO concentration (mg/l) at Vinca and the Low Level Bridge in time (T_1) days. This equation was based on specific conditions of BOD loading, discharge and river velocities, and its usage may be restricted to these or similar conditions.



CHAPTER VIII

RECOMMENDATIONS

1. Time-of-Travel Measurements

In order to establish an accurate record of travel times required for a slug of water to pass through the study area, a comprehensive program of mean velocity measurements at different discharges should be undertaken over an entire winter period. Dye tracing studies should be carried out through the entire study area, which must be divided into many short reaches. The use of short reaches (10 to 20 miles long) facilitates greater economy in dye usage, and reduces the chances of dye adsorption to organic matter in suspension or on the channel bottom.

Because of the low cost and sorptive tendency of fluorescein, use of this dye is recommended as a soluble contaminant tracer in travel time studies conducted under ice-cover conditions. Because of the low photochemical decay rate of rhodamine B, this dye is recommended for studies carried out in open water conditions. The Turner Model III fluorometer, as used in this study, readily detects dye concentrations in the river as low as 0.5 ppb and is recommended for use in time-of-travel studies.

Computer applications should be used in the analysis of data collected in the dye tracing studies. The mathematical integration and analysis of the time-concentration data from each sampling point will give (1) the discharge of the river at the time of testing, (2) the travel time of the dye wave centroid (considered to be the average travel time of the dye to the sampling point), (3) the longitudinal dispersion characteristics of the reach being tested, and (4) the amount of dye that may be lost through natural dilution, adsorption to organic matter, chemical action or photochemical decay. The measurement of dye loss may be representative of the factors involved in the removal of organic matter (BOD) from the water phase.

2. Future Studies

If a separate study of velocity measurements, could be undertaken, as discussed above, a greater amount of time would be available for a more comprehensive sampling program. It is felt that with a greater number of sampling runs taken at different discharges, conclusive rates of deoxygenation and BOD removal could be established.

Other areas open to further research in bio-oxidation relationships under ice-cover in the North Saskatchewan River are:

1. The effects of discharge on the rate of D₀ utilization (K value in equation 9), the rate of deoxygenation (K_d) and the rate of BOD removal (K_r) .
2. The rate and extent of bottom deposit build-up during periods of low winter flows. A comprehensive program of "basket" sampling, as started by Cameron (1967), should be carried on throughout the entire study area.
3. The effect of additional heated cooling water effluent being discharged to the river from the Clover Bar Power Plant, when it commences operation in the fall of 1970. This heated effluent will increase the length of open water up to or past the Fort Saskatchewan Bridge. The increased stretch of open river will probably increase reaeration of the river downstream from Edmonton. Increased water temperatures downstream from the plant may increase biological activity, resulting in a greater D₀ demand being exerted within the reach. This higher oxygen demand, depending on the extent of further reaeration, may or may not change the point where deoxygenation in the river presently commences (one to two days downstream from the Low Level Bridge). The rates of deoxygenation and BOD removal, as well as the BOD loadings in the river immediately downstream from Edmonton, as determined from this study, will undoubtedly be affected by the addition of this heated effluent to the river.
4. The flow velocity required to scour settled organic matter from the channel bottom. Depending on the amount of biological activity and density of

accumulated deposits, Velz (1949) showed that scouring took place at flow velocities between 1.0 to 1.5 fps. Based on this, the velocities encountered in this study would be capable of scouring bottom deposits.

Continuation of this study is encouraged. If the aforementioned studies are carried out, an accurate formulation of DO utilization and BOD removal under ice-cover conditions is possible. Knowledge of the waste assimilation capacity of the river under ice-cover conditions would be instrumental in carrying out an effective pollution abatement program.

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A P P E N D I X A

APPENDIX A

THEORY OF THE DISSOLVED OXYGEN PROFILE
AND BIOCHEMICAL OXYGEN DEMAND1. Introduction

The oxygen deficiency in a stream at any point is the resultant of two opposing processes, each governed by a different set of conditions - one consuming oxygen from the stream and the other replenishing the oxygen source, both processes proceeding as a time function in accordance with definite laws (Purdy 1968).

2. The Dissolved Oxygen Profile

The classical theory of Streeter and Phelps (1925) has proven to be invaluable in evaluating the ability of streams to assimilate organic pollution. This theory is based on the two independent processes of biochemical oxidation of organic matter and reaeration through surface absorption from the atmosphere. The two processes are generally described according to the following first-order equation:

$$\frac{dD}{dt} = k_1 L - k_2 D \quad (1)$$

This basic differential equation states that the net rate of change in the DO deficit ($\frac{dD}{dt}$) is equal to the sum of (1) the rate of oxygen utilized by BOD in the absence of reaeration (K_1L) and (2) the rate of oxygen absorption by reaeration in the absence of BOD ($-K_2D$). K_1 and K_2 are, respectively, the coefficient of deoxygenation and reaeration (per day), while L is the concentration of the organic matter (mg/l) and D is dissolved oxygen deficit (mg/l) at any time t .

Since the Streeter-Phelps equations were first presented, many investigators have listed several additional sources of oxygen supply and demand. Dobbins (1964) has suggested that some or all of the following processes may be taking place in any given river stretch:

1. The removal of BOD by sedimentation or adsorption.
2. The addition of BOD along the stretch by the scour of bottom deposits or by the diffusion of partly decomposed organic products from the benthic layer into the water above.
3. The addition of BOD along the stretch by local runoff.
4. The removal of oxygen from the water by diffusion into the benthic layer to satisfy the oxygen demand in the aerobic zone of this layer.
5. The removal of oxygen from the water by purging action of gases rising from the benthic layer.

6. The addition of oxygen by the photosynthetic action of plankton and fixed plants.
7. The removal of oxygen by the respiration of plankton and fixed plants.
8. The continuous distribution of both the BOD and oxygen by the effect of longitudinal dispersion.

Various modifications to the basic Streeter-Phelps equation have been proposed in order to take into account some of the previously listed processes. Thomas (1948) proposed the introduction of a rate constant, K_3 , as a means of accounting for the removal or addition of BOD by deposition or resuspension. The net rate of deposition was assumed to be proportional to K_3L , a positive value indicating deposition and a negative value indicating resuspension. O'Connor (1961) introduced the effect of longitudinal dispersion and demonstrated its importance in slow-moving, highly mixed streams such as estuaries. Velz and Gannon (1964) discussed the mechanics of "abnormal" BOD removal consisting of two independent processes acting simultaneously. These two processes were normal biochemical oxidation and biological extraction or separation by bio-physical contact. Depending on channel characteristics, the mechanics of biological extraction of BOD is analogous to either trickling filters or activated sludge systems.

Dobbins (1964) combined the results of several writers to develop a pair of second-order partial differential equations to describe the BOD and DO profiles.

The development of these equations was based on the following assumptions:

1. The stream flow is steady and uniform.
2. The process for the stretch as a whole is a steady-state process, the conditions at every cross section being unchanged with time.
3. The removal of BOD by both bacterial oxidation and the sedimentation or adsorption or both are first order reactions, the rates of removal at any section being proportional to the amount present.
4. The removal of oxygen by the benthal demand and by plant respiration, the addition of oxygen by photosynthesis, and the addition of BOD from the benthal layer or the local runoff are all uniform along the stretch.
5. The BOD and oxygen are uniformly distributed over each cross section, thus permitting the equations to be written in the usual one-dimensional form.

Using the foregoing assumptions, Dobbins represented the BOD and DO profile along a stretch of a polluted stream by the following differential equations:

$$D_L \frac{d^2 L}{dx^2} - U \frac{dL}{dX} - (K_1 + K_3)L + L_a = 0 \quad (2)$$

$$D_L \frac{d^2 C}{dx^2} - U \frac{dC}{dX} - K_1 L + K_2 (C_s - C) - D_B = 0 \quad (3)$$

in which L = the first stage BOD (mg/l) ; C = dissolved oxygen concentration (mg/l) ; D_L = the coefficient of

longitudinal dispersion (sq miles per day); U = the average stream velocity (miles per day); K_1 = the BOD reaction rate coefficient (per day); K_3 = the rate coefficient for the removal of BOD by sedimentation and adsorption or both (per day); L_a = the rate of addition of BOD along the stretch (mg/l per day); K_2 = the re-aeration rate coefficient (per day); D_B the net rate of removal of dissolved oxygen by all processes other than the biochemical oxidation of the flowing BOD load (mg/l per day); X = distance along the stretch (miles); t = time (days); and C_s = the saturation dissolved oxygen concentration (mg/l).

The solutions of equations (2) and (3) illustrate that the BOD profile (equation 2) is independent of the DO profile (equation 3), while the DO profile is dependent on the BOD profile. In equations (2) and (3) the rate of BOD removal by biochemical oxidation is represented by K_1L and the rate of extraction of BOD by sedimentation and adsorption or both to the stream bed is represented by

K_3L . The term L_a accounts for the possible addition of BOD along the stretch by local runoff or by the diffusion of partly decomposed organic products from the benthic deposits. The term D_B represents the net oxygen demand of benthic deposits, removal of oxygen by algal and fixed plant respiration and introduction of oxygen by photosynthesis.

Based on the initial assumption of steady state conditions, the negligible effect of longitudinal dispersion, and the application of appropriate boundary conditions, equations (2) and (3) may be rewritten as:

$$L = L_A e^{-(K_1 + K_3)t} + \frac{L_a}{K_1 + K_3} \left(1 - e^{-(K_1 + K_3)t} \right) \quad (4)$$

and

$$D = \frac{K_1 \left(L_A - \frac{L_a}{K_1 + K_3} \right) (e^{-(K_1 + K_3)t} - e^{-K_2 t})}{K_2 - (K_1 + K_3)} + D_0 e^{-K_2 t} + \left(\frac{D_B}{K_2} + \frac{K_1 L_a}{K_2 (K_1 + K_3)} \right) (1 - e^{-K_2 t}) \quad (5)$$

When L_a , K_3 and D_B are set equal to zero, equations (4) and (5) revert to the Streeter-Phelps equations. Camp (1965) developed a similar equation to that of Dobbins (equation 5) but expressed concern over the difficulty and expense required to predict all the rate constants. Thackston and Krenkel (1969) felt that the rate constants cannot be measured directly in a polluted stream because it is quite difficult to separate the effects of several processes that are occurring simultaneously. Many investigators are involved in the expansion and refinement of the D0-BOD profile equations by use of mathematical models in order to predict reasonable rate

constants. Some of these writers, mentioned for further references, are Metzger (1968), Bella and Dobbins (1968), Dresnack and Dobbins (1968), and DiToro (1969).

3. Biochemical Oxygen Demand

Biochemical Oxygen Demand (BOD) is generally defined as the amount of oxygen required by bacteria while stabilizing decomposable organic matter under aerobic conditions (Sawyer and McCarty, 1967). The biological breakdown (stabilization) of organic matter, under aerobic conditions, generally proceeds through two stages: (1) a first stage in which heterotrophic bacteria utilize the carbonaceous matter for its food source, and (2) a second stage in which nitrifying bacteria utilize the nitrogenous matter for its food source.

The kinetics of aerobic decomposition for the carbonaceous stage is generally unimolecular or first-order in nature; that is, the rate of the reaction is proportional to the amount of oxidizable organic matter remaining at any time. That is:

$$-\frac{dL}{dt} = KL \quad (6)$$

which, when integrated, yields:

$$y = L(1 - 10^{-Kt}) \quad (7)$$

where y = BOD (mg/l) at any time t , L is the total or ultimate first stage BOD, (mg/l), K is the rate constant of reaction (per time).

In conducting a regular BOD test at 20°C on freshly polluted water, the first, or carbonaceous, stage extends to about the tenth day when the BOD exerted relative to the BOD remaining at any given time becomes substantially constant (Fair and Geyer, 1967). In eight to ten days, the nitrifying bacteria population begins to exert an appreciable demand for oxygen. This results in a sharp rise in BOD and signifies the commencement of the second, or nitrogenous stage. To eliminate the interference of the nitrifying bacteria, the 5 day incubation period has been selected for the standard BOD test.

The BOD profile of a stream, as formulated by Dobbins (1964), is given in equation (4). The total BOD demand in streams is made up of: (1) the normal oxidation of organic matter in the stream flow, (2) the oxidation of the aerobic layers of sludge deposits, (3) the oxidation of accumulated or extracted material, and (4) the oxidation of nitrogenous substances to nitrates. Associated with each of these factors are the individual BOD rates, which have been subject to investigation by various writers. Kittrell and Kochtitzky (1947) suggested that rapid BOD reduction could be found due to the adsorption of organic matter in biological slimes. Velz (1949) presented data to support the premise that organic sludge will deposit at a critical velocity of about 0.6 fps and

scouring will take place at about 1.0-1.5 fps, depending upon activity of decomposition and compaction of accumulation. Velz and Gannon (1964) presented and verified a working theory on the mode of action of biological extraction and accumulation in stream self-purification. Nejedly'(1966) reported on the effect of transverse and longitudinal mixing which caused increased BOD reduction due to increased contact opportunity. Wezernack and Gannon (1968) in a study of the Clinton River in Michigan illustrated the impact of nitrification on stream oxygen resources. They outlined the necessity for including inorganic nitrogen oxidation in the total BOD of a stream.

4. Dissolved Oxygen

Most living organisms are dependent upon oxygen in one form or another to maintain the metabolic processes that produce energy for growth and reproduction (Sawyer and McCarty, 1967). In waters containing organic matter undergoing decomposition or decay, the presence or absence of dissolved oxygen will determine whether or not biological changes are brought about by aerobic or anaerobic organisms. In the control of natural waters receiving pollutional matter, an adequate level of free oxygen must be maintained for proper growth and reproduction of all aquatic flora and fauna.

Atmospheric oxygen is considered to be relatively insoluble in water and thus its solubility is proportional

to its partial pressure (Henry's Law). The saturation content of dissolved oxygen in natural water depends on: (1) the water temperature, (2) the saturated vapor pressure of the water at the temperature of the water, (3) the barometric pressure (altitude) of the point in question and, (4) the salinity or chloride content of the water.

Fair and Geyer (1967) suggest the following empirical equations to calculate the saturated value of dissolved oxygen in water:

Between 0°C and 30°C ,

$$C_s = 0.678 (p - p_w) (1 - n \times 10^{-5}) / (T + 35) \quad (8)$$

Between 30°C and 50°C

$$C_s = 0.827 (p - p_w) (1 - n \times 10^{-5}) / T + 49 \quad (9)$$

Where C_s is the dissolved oxygen saturation value (mg/l),

p is the barometric pressure, or altitude of the collecting point, p_w is the saturated vapor pressure of water at that temperature, n is the salinity or chloride content (mg/l), and T is the water temperature ($^{\circ}\text{C}$).

A P P E N D I X B

APPENDIX B

DISSOLVED OXYGEN ANALYZER ANALYSIS

A Union Carbide Model 1101 Dissolved Oxygen Analyzer and a Leeds and Northrup Speedomax M Mark II Recorder were purchased to provide a portable method of measuring DO concentrations in the river at various locations during the study program. A description of the equipment is outlined in Chapter IV.

As mentioned in Chapter IV, a considerable amount of time and effort was expended in an attempt to calibrate the analyzer for field use. Several problems were experienced in both the initial calibration phase and during the time the equipment was used in the field. A few of these problems, considered to be pertinent in the consideration of this equipment for future use, are outlined below.

When the equipment was received from the manufacturer, both temperature and DO readings went off scale. In checking the electronic circuitry, as outlined in the operating manual, it was determined that the analyzer did not respond to the DC millivolt output of the probe. Follow-

ing the procedures outlined in the operating manual, an attempt was made to calibrate the analyzer to respond to the probe output. Some of the problems noted during this time were:

1. When the instrument was calibrated using the calibration curve supplied with the operating manual, the analyzer did not respond to known DO concentrations (determined by the Modified Winkler Method). When it was determined that the probe required a higher velocity of flow to produce a steady output, a digital voltmeter was used to establish the probe output corresponding to known DO concentrations. A calibration curve was drawn up and the instrument was calibrated from this curve when it was determined that the curve in the operating manual did not correspond to that determined in the laboratory.
2. The calibration curve found in the operating manual is for a standard probe containing a silver-silver chloride reference electrode. The probe supplied with the equipment contained a different type of reference electrode, as confirmed by company representatives during a visit in April, 1970. It was then suggested that the company should provide separate calibration curves for each probe it sells.
3. The probe, in order to supply a steady and reliable DC output to the analyzer, required a minimum flow velocity of 4 fps past the probe. This is contrary to the manufacturer's claim that only "slightly" agitated water is required.

4. The temperature response, at lower temperatures of $0-5^{\circ}\text{C}$ was, at best, within $+1.5^{\circ}\text{C}$. A visit by company representatives in April, 1970 confirmed that low temperatures in combination with hard, sea or highly conductive water are a problem. The operating manual and supporting literature claim a response of $\pm 0.5^{\circ}\text{C}$ at 0°C .

Since the probe required a fairly high velocity (4 fps), its usage was confined to raw water supply lines. In an attempt to measure the DO concentrations in the river upstream from the cooling water effluent, and prior to the river receiving domestic and industrial wastes from Edmonton, the analyzer and recorder were installed in the City of Edmonton Power Plant Pump House No. 2. The DO concentrations measured at this point are indicative of the DO levels under ice cover upstream from Edmonton. The instrument was in operation from January 15 to March 4, 1970 and during this time some of the problems noted were:

1. After the initial set-up, nearly one week was required for the instrument to provide steady and reliable readings. Any sudden interruption in the normal flow past the probe caused erratic fluctuations, and up to two days were required for the instrument to settle down and provide reliable readings.
2. The pressure of the raw water line (15-20psi) forced the reference electrode out of the probe on several occasions. This problem was solved by wrapping friction tape around the reference electrode at the point where the compression o-ring sealed the electrode to the probe.

3. The ink supply to the chart was found to clog and dry in the pen point. This was solved by diluting the ink and filing the pen point. The ink supply in the recorder required replenishing every five to six days.

From the aforementioned observations, it can be seen that the DO analyzer cannot properly measure DO concentrations at flows less than 4 fps at temperatures between 0-5°C. The analyzer has limited use in a study of this kind and it is felt that further refinement is required before the analyzer can meet manufacturer's claims. On the other hand, the recorder provided reliable and accurate measurements and its use with the DO analyzer is recommended.

A P P E N D I X C

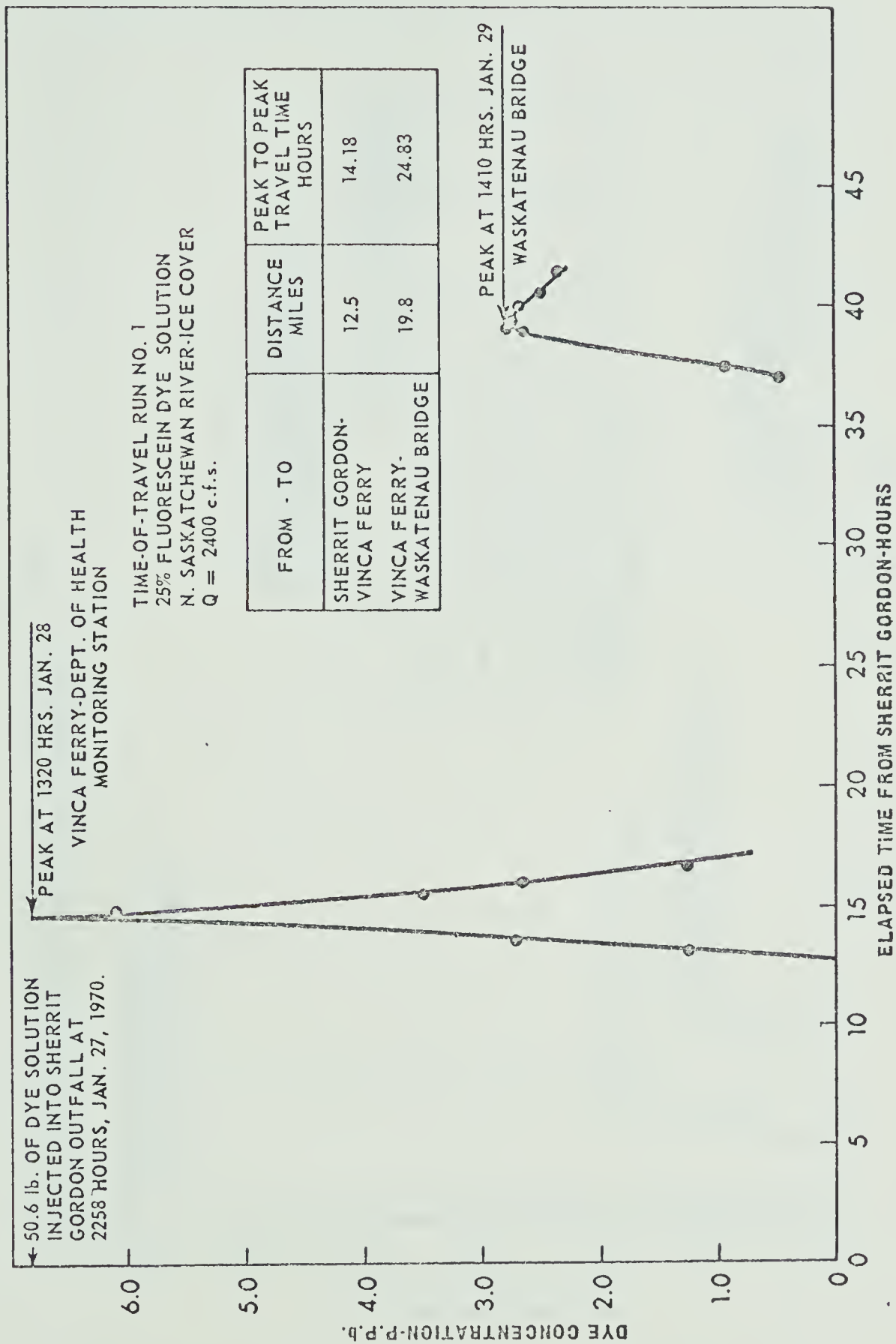
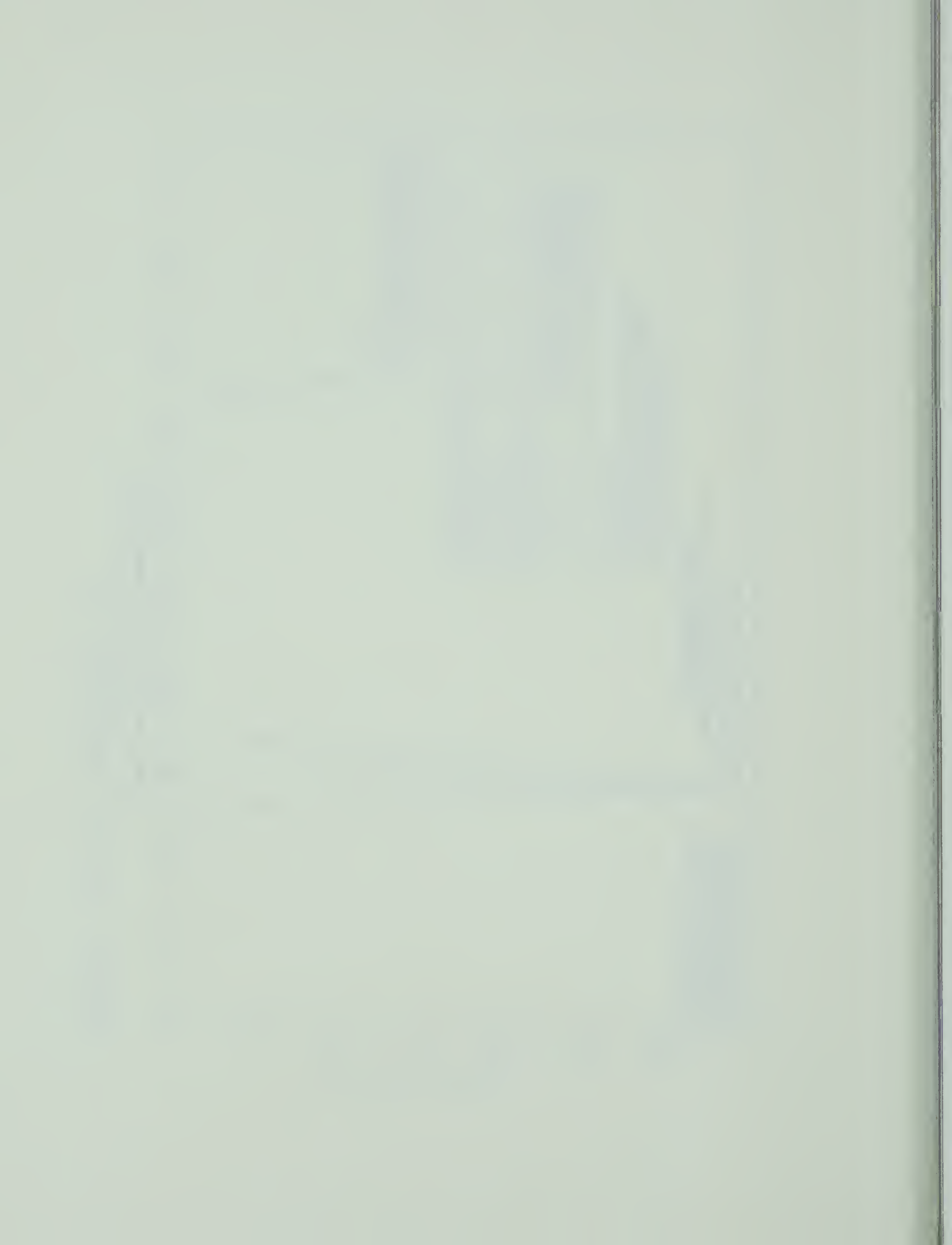


FIGURE C1: TIME - OF - TRAVEL STUDY - NO. 1



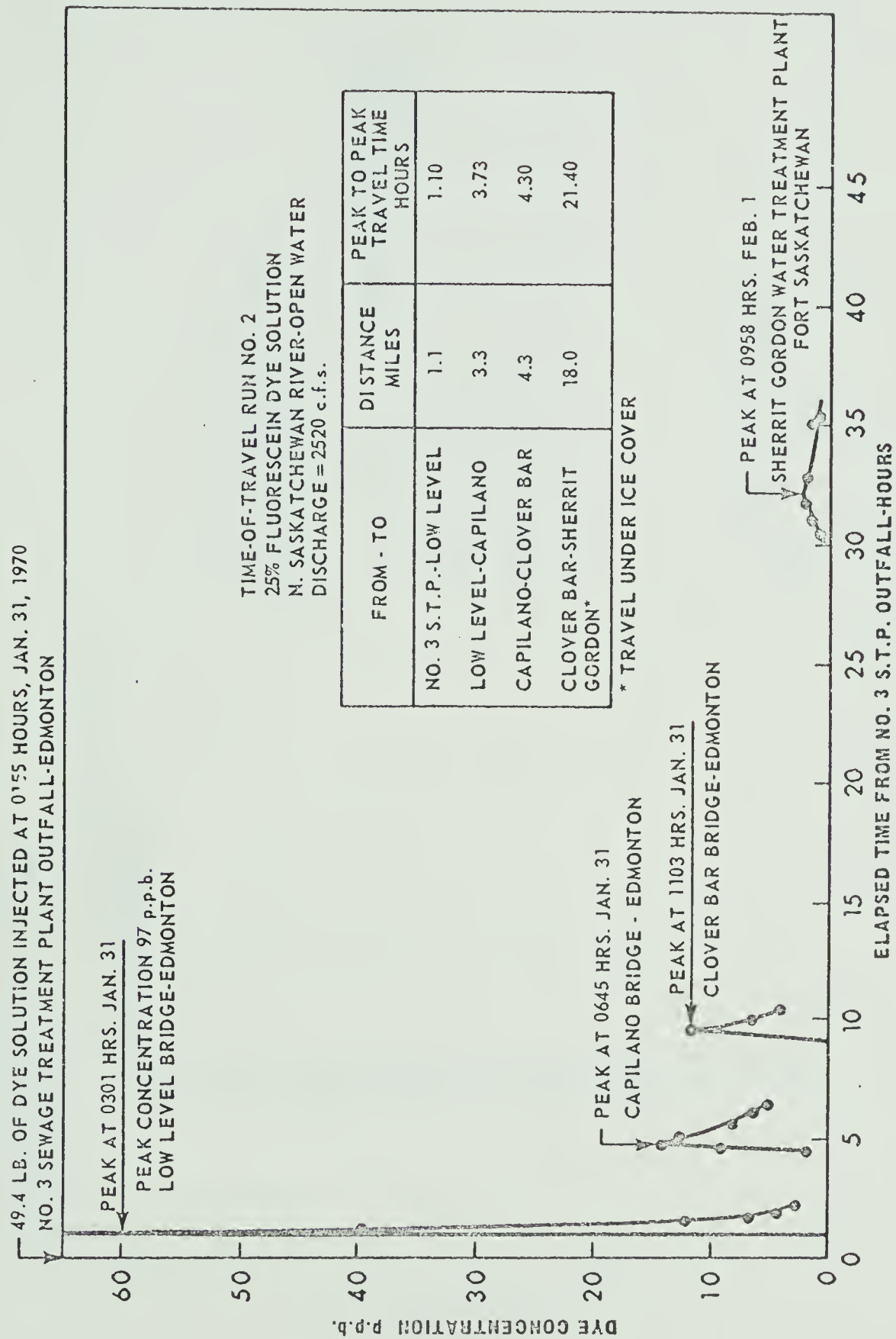


FIGURE C2: TIME-OF-TRAVEL STUDY NO. 2



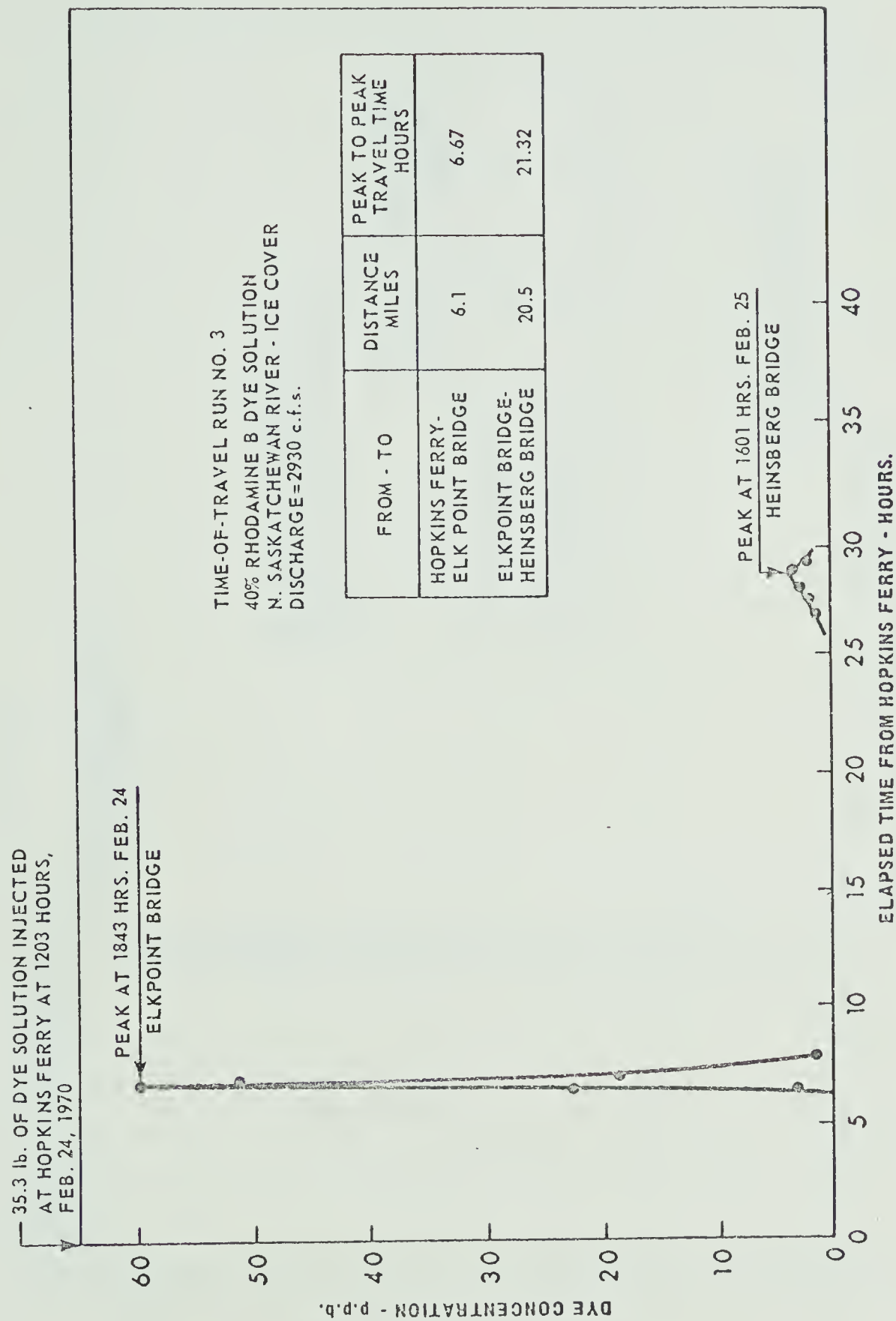


FIGURE C3: TIME-OF-TRAVEL STUDY NO. 3

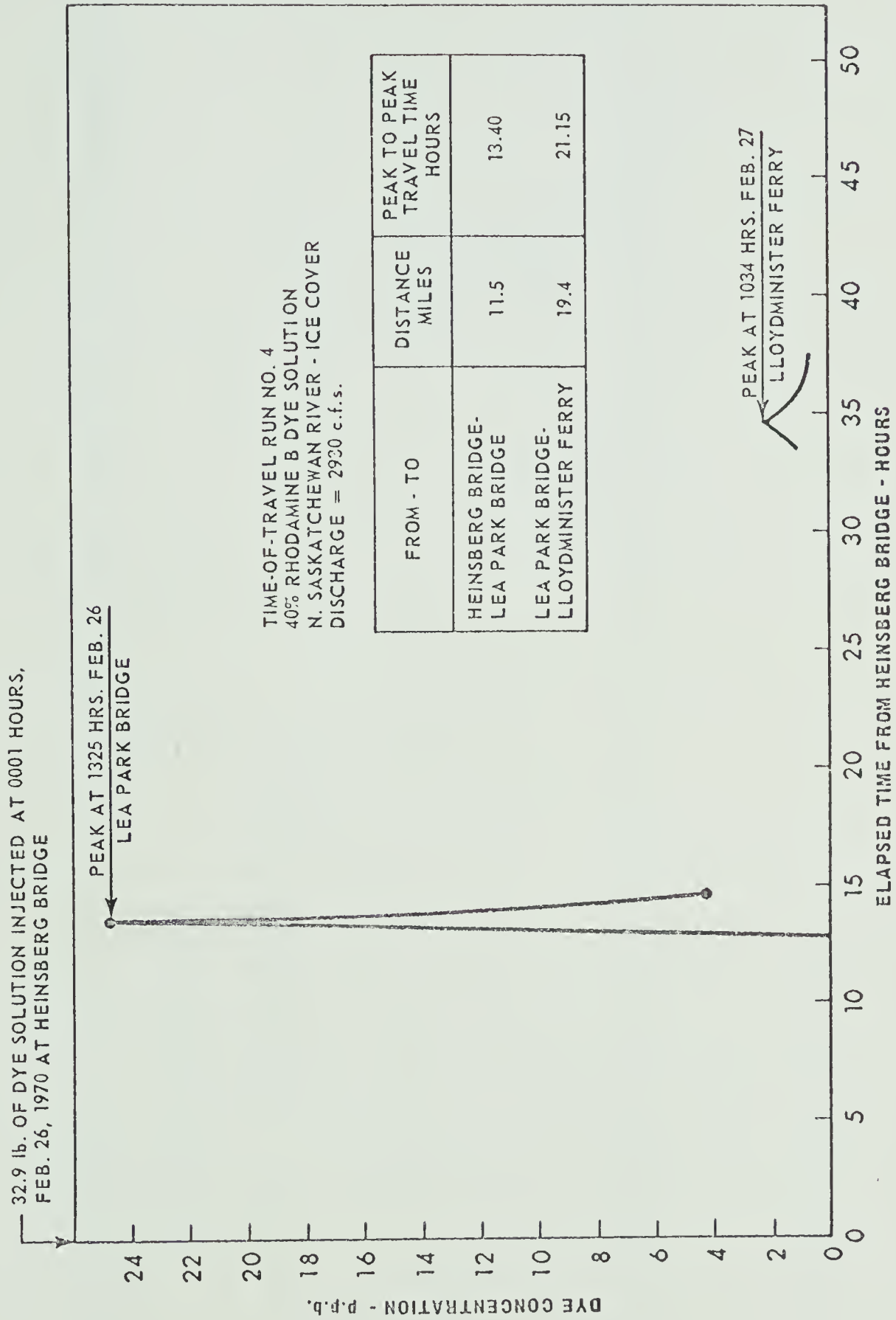
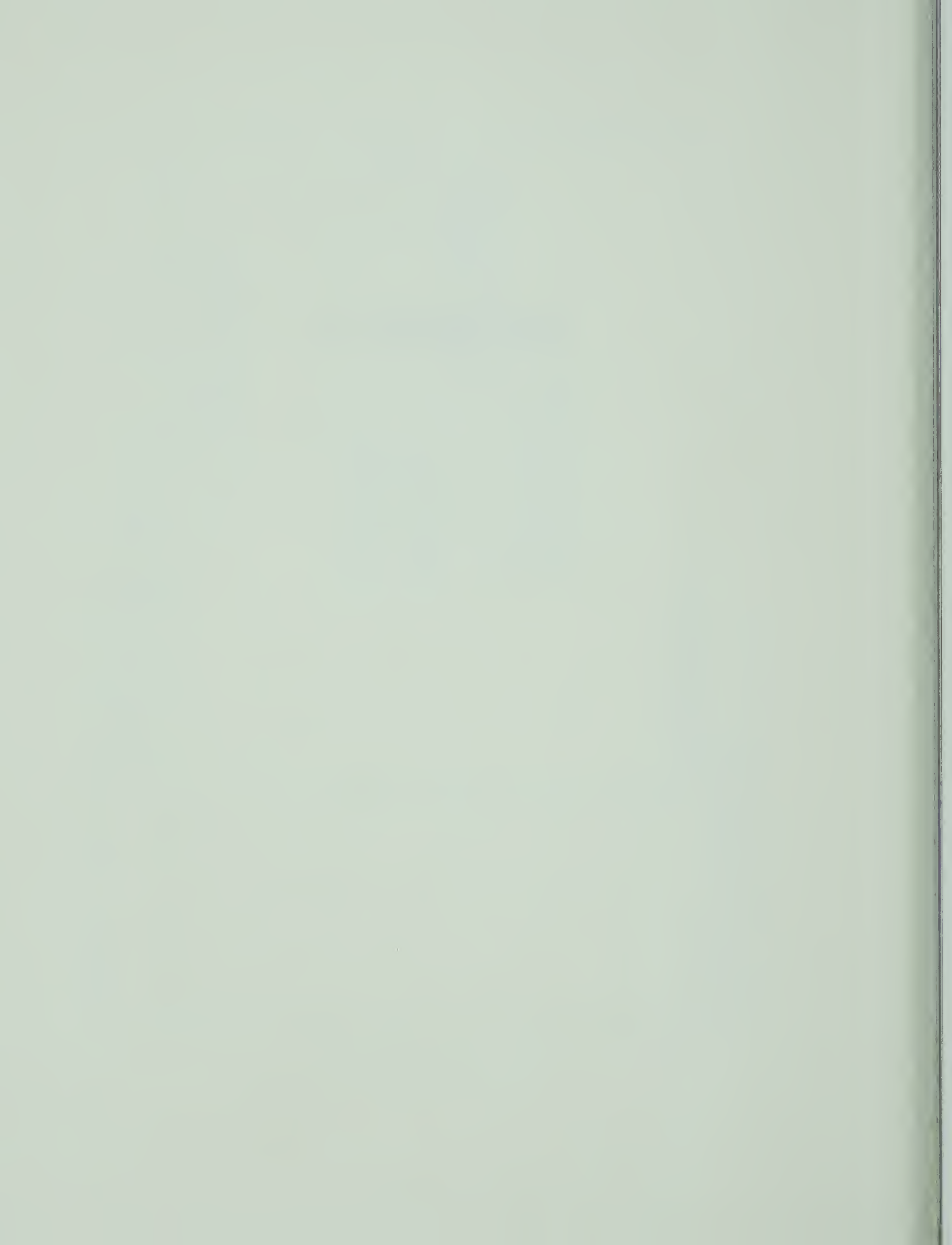


FIGURE C4: TIME-OF-TRAVEL STUDY - NO. 4

A P P E N D I X D





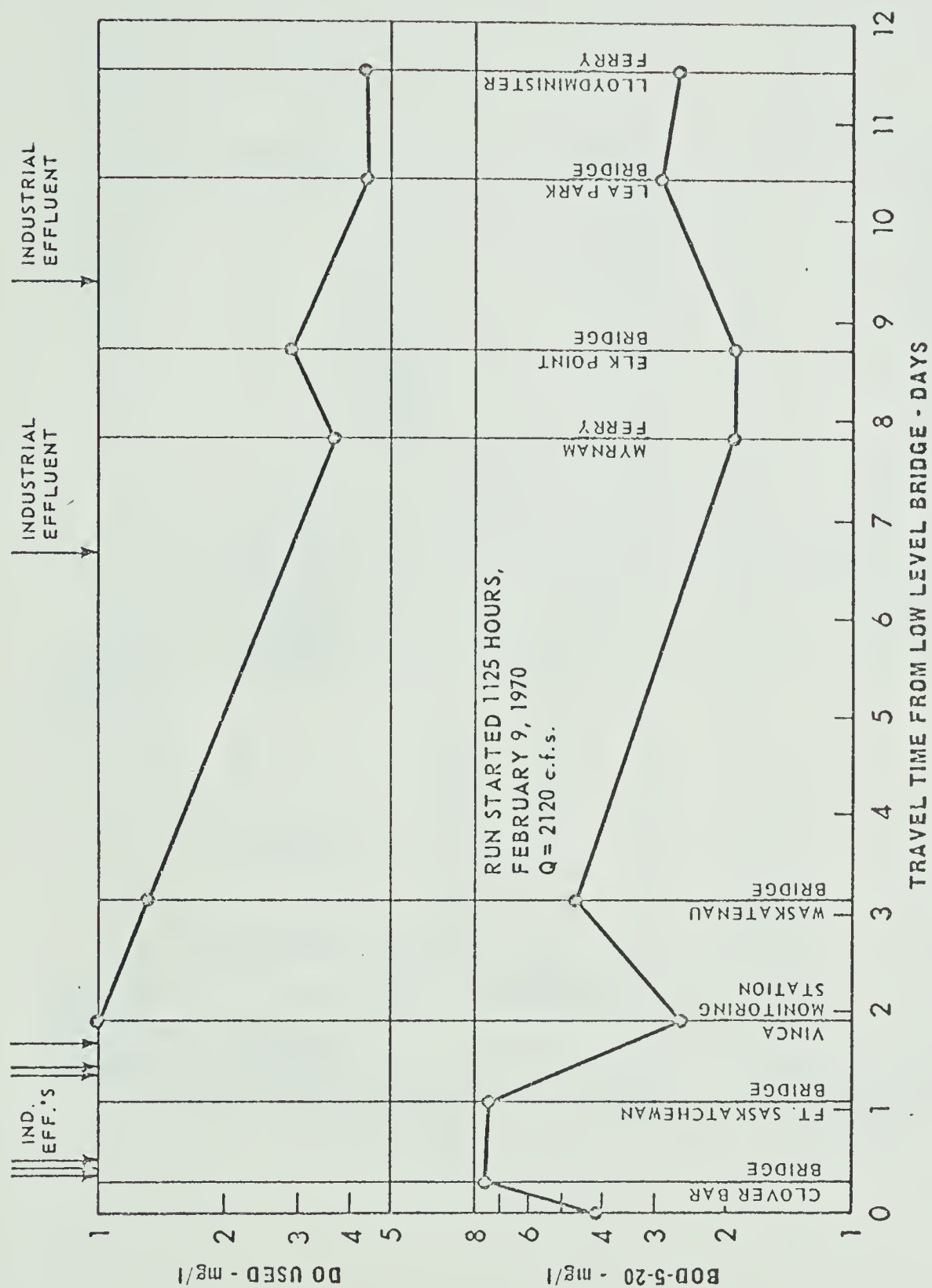


FIGURE D2: BOD - DO UTILIZATION CURVES



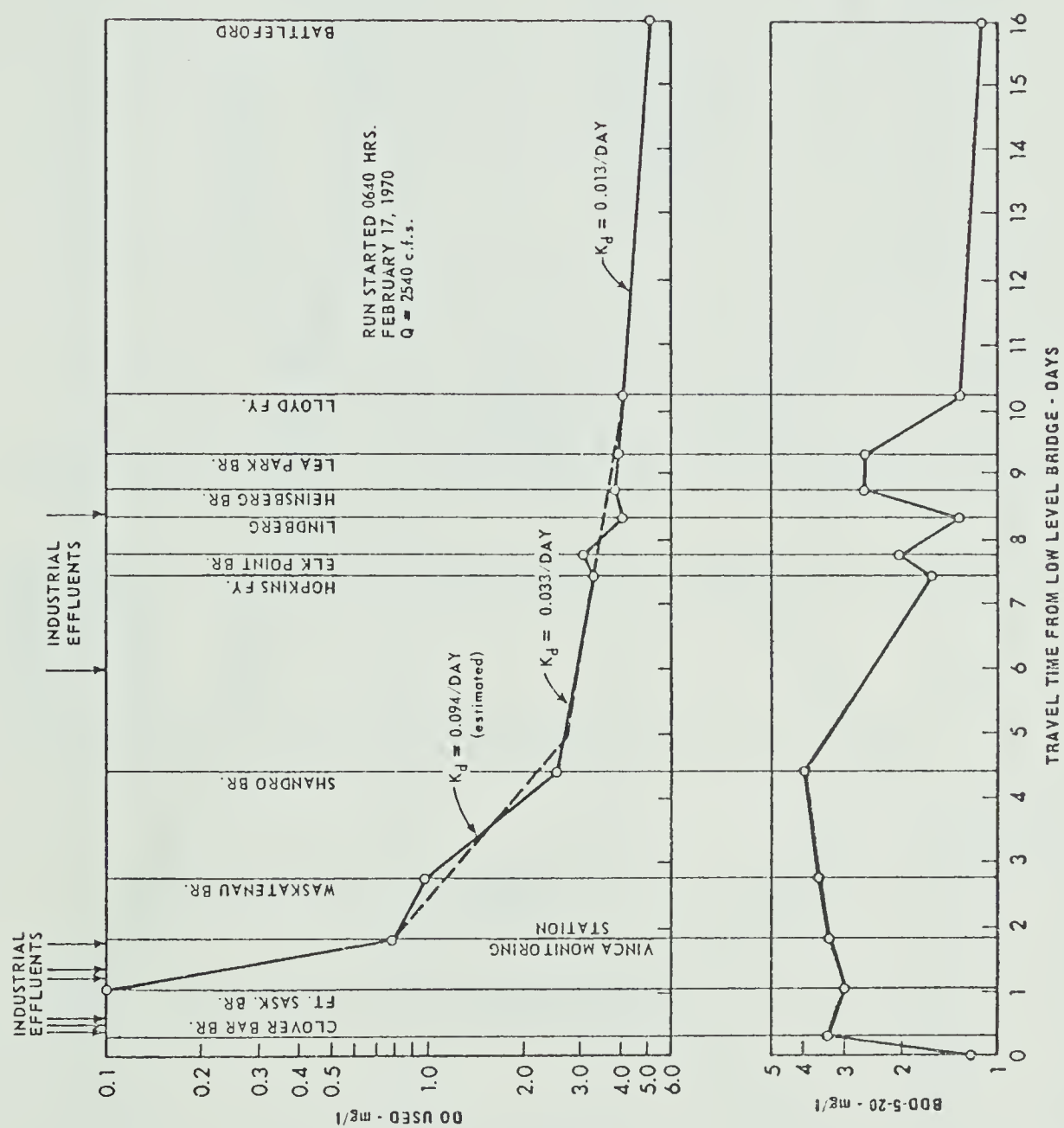


FIGURE D3: BOD - DO UTILIZATION CURVES



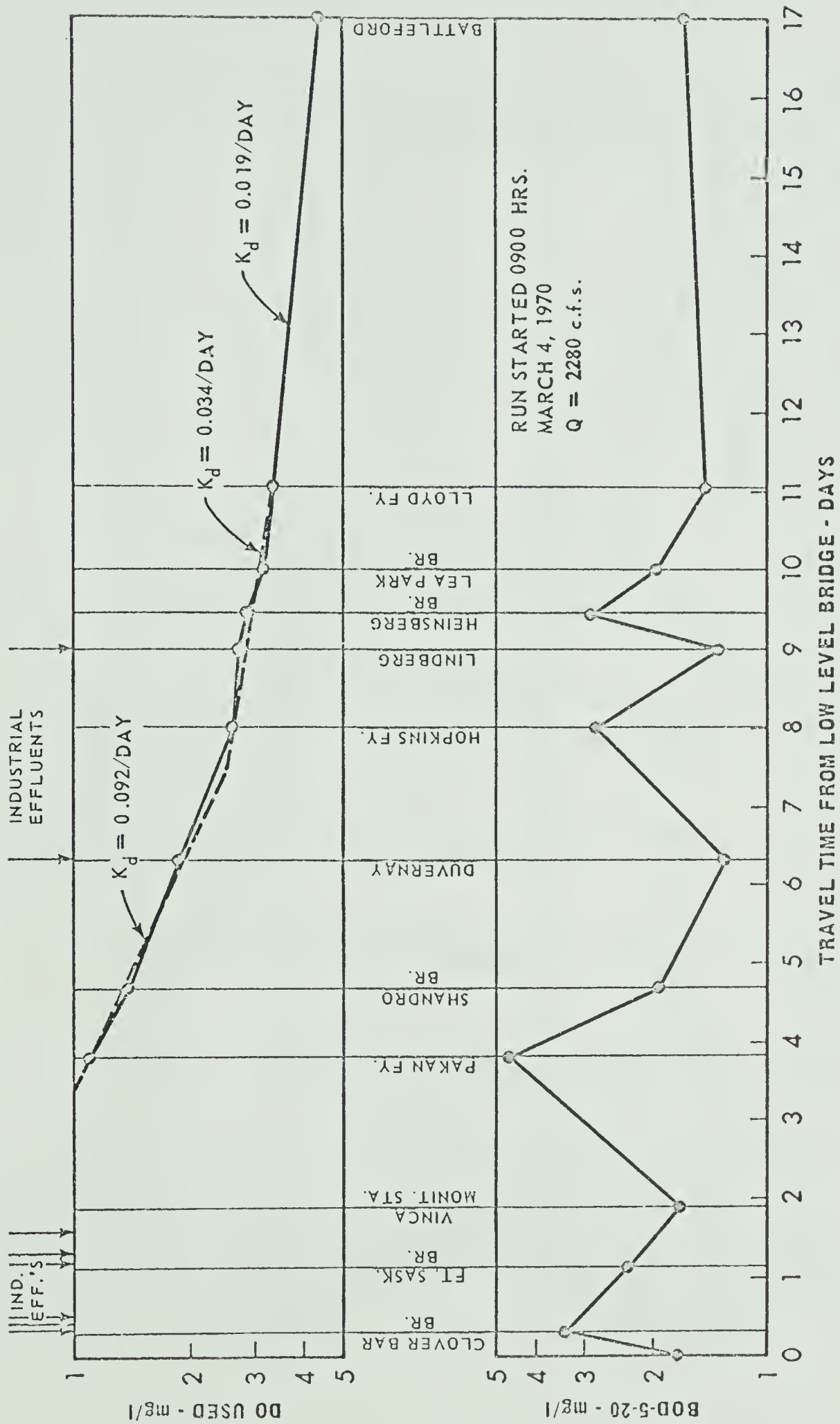


FIGURE D4: BOD - DO UTILIZATION CURVES

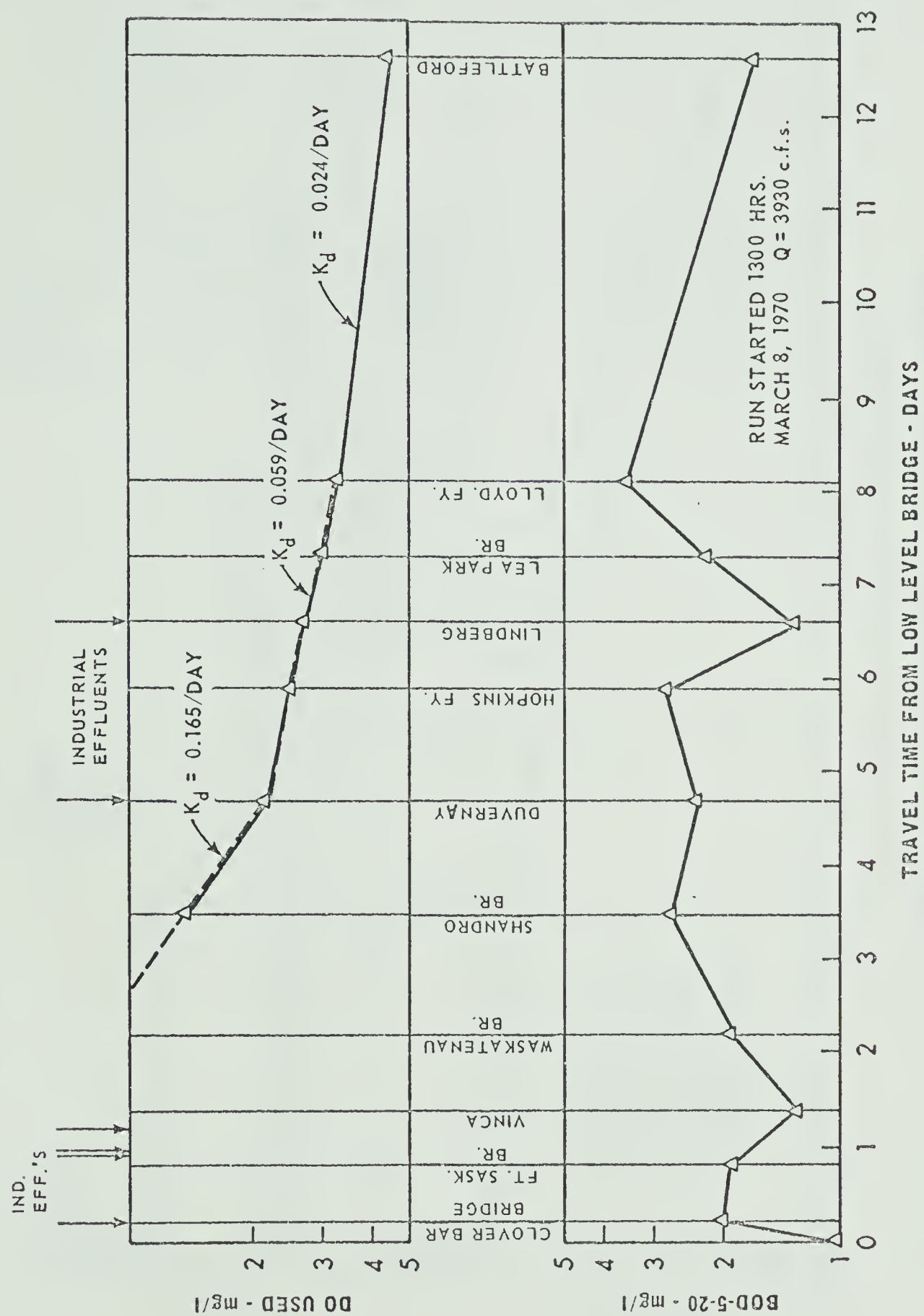


FIGURE D5: BOD - DO UTILIZATION CURVES

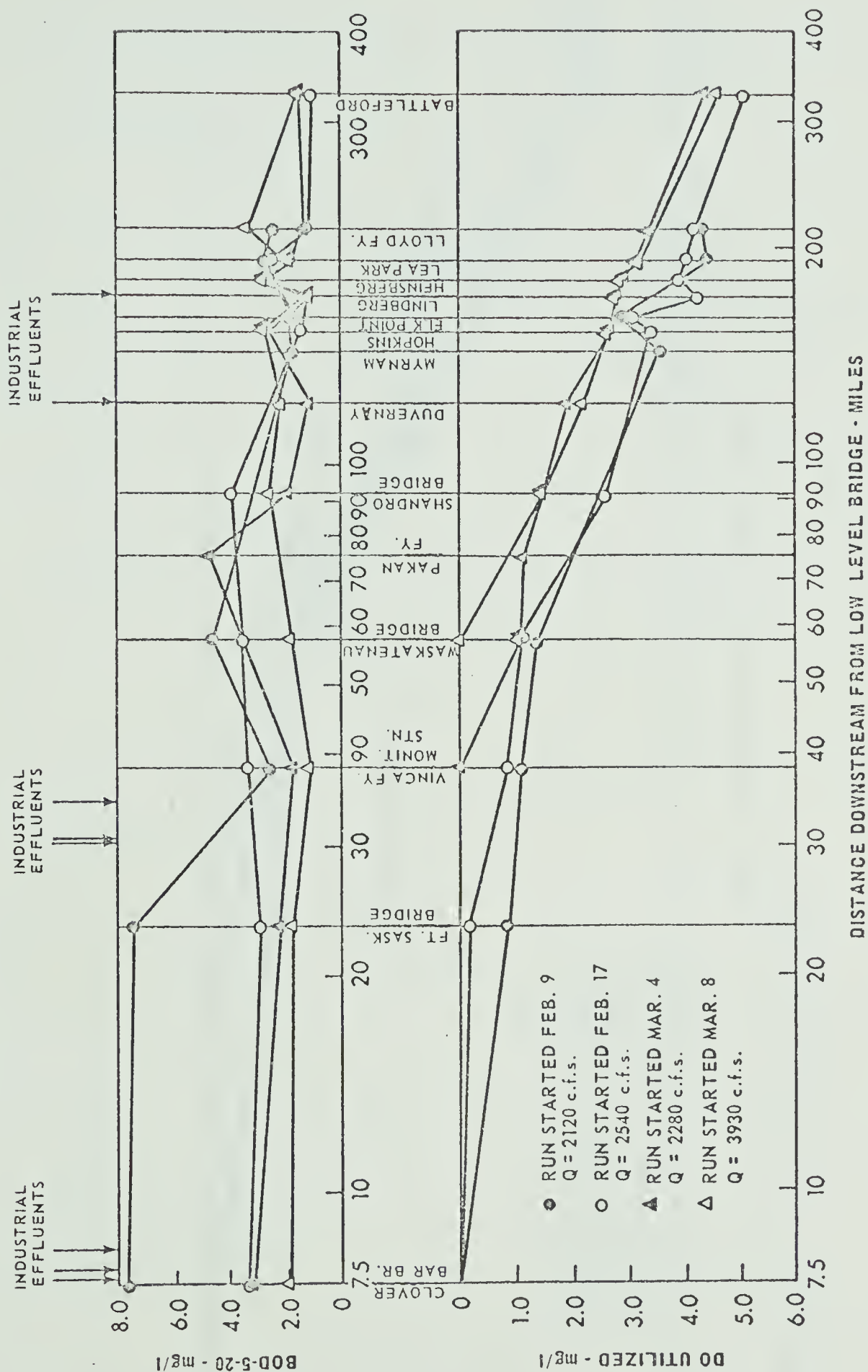


FIGURE D6: BOD - DO UTILIZATION IN THE NORTH SASKATCHEWAN RIVER
FEBRUARY AND MARCH 1970

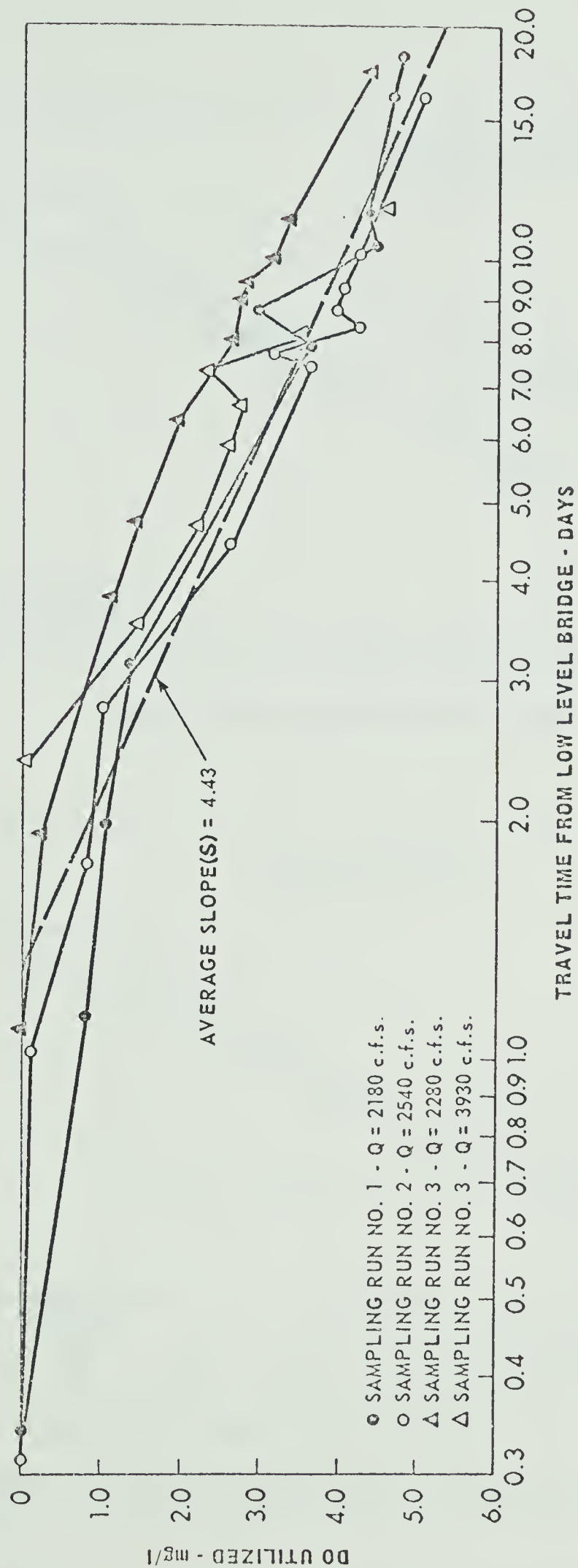


FIGURE D7: DO UTILIZATION CURVES

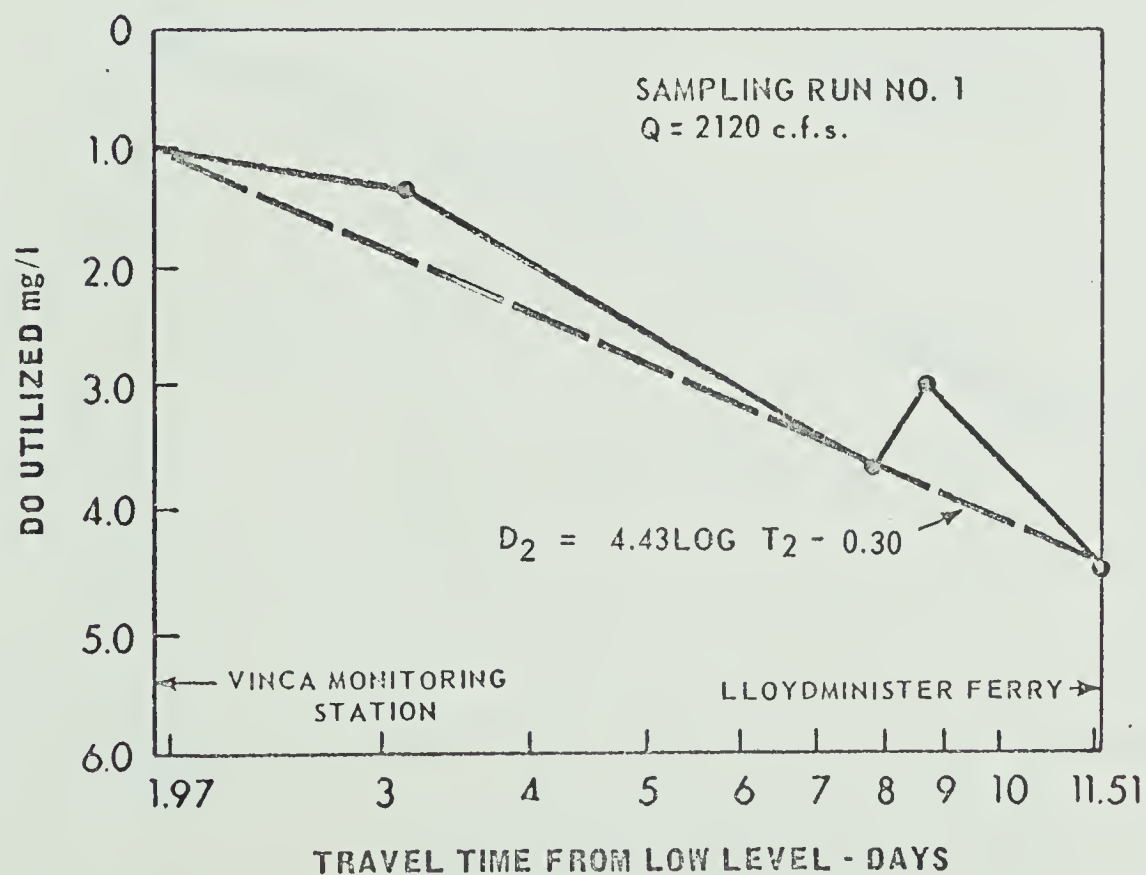
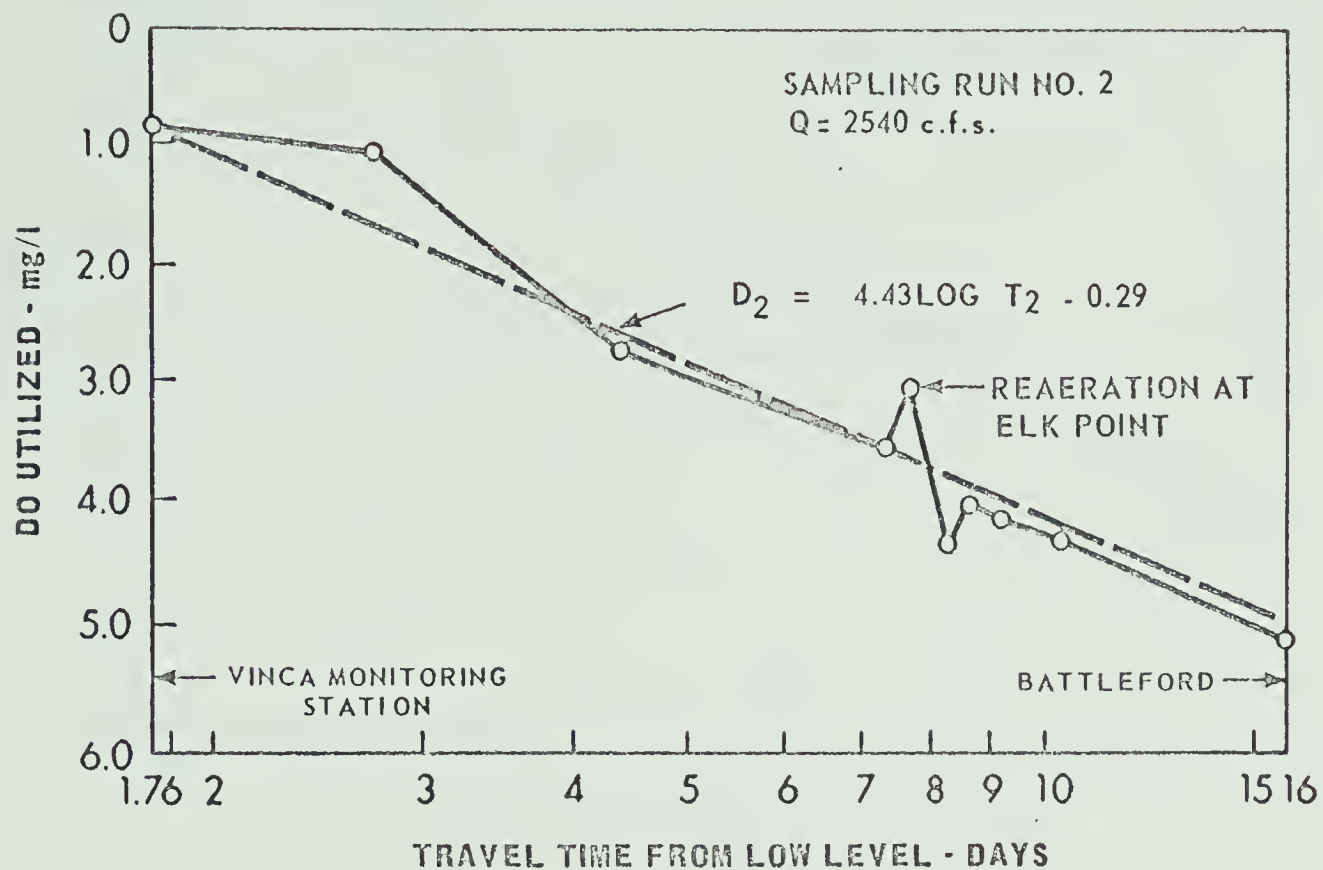


FIGURE D8: DO UTILIZATION CURVES - FEBRUARY 1970

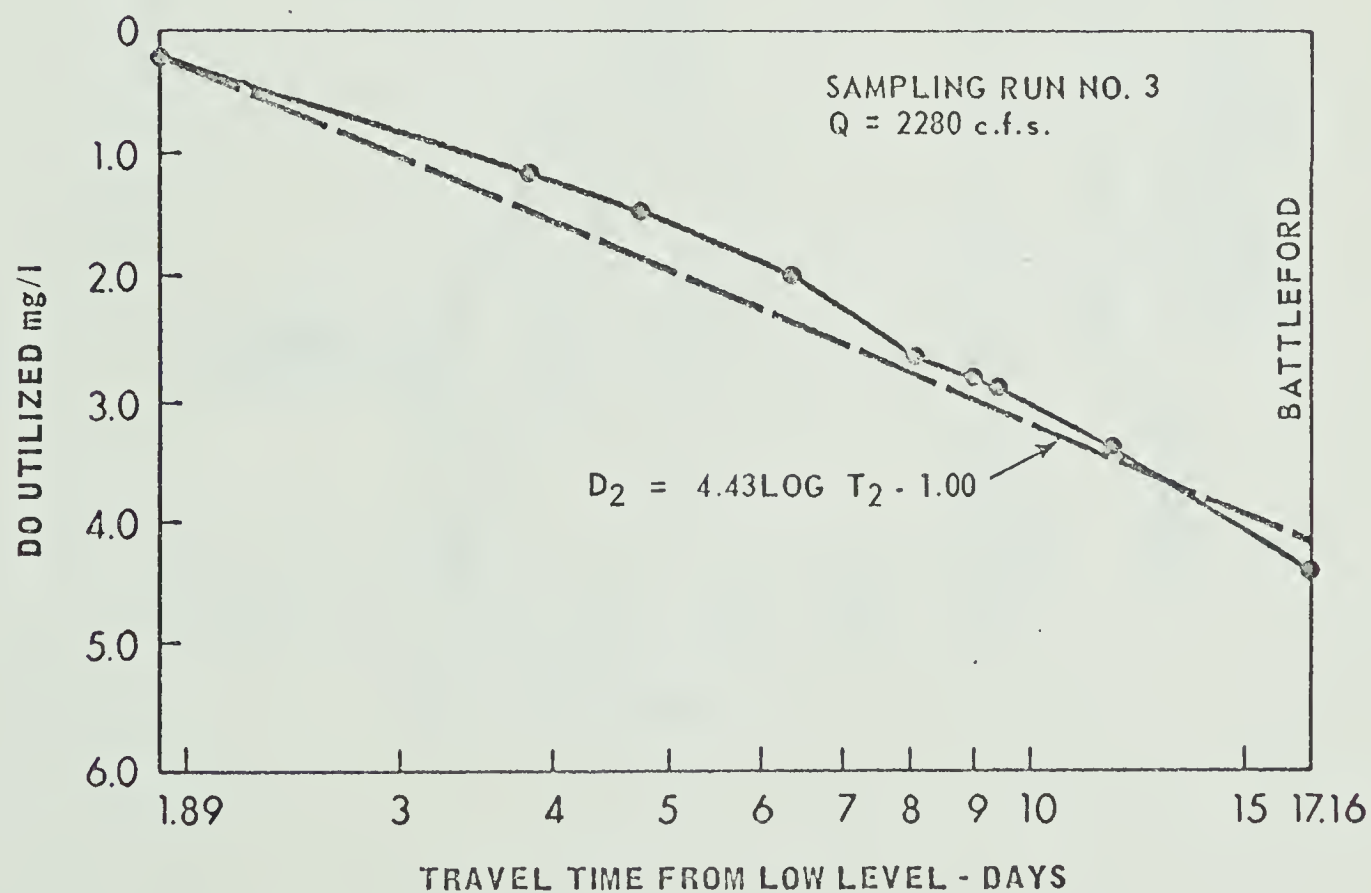
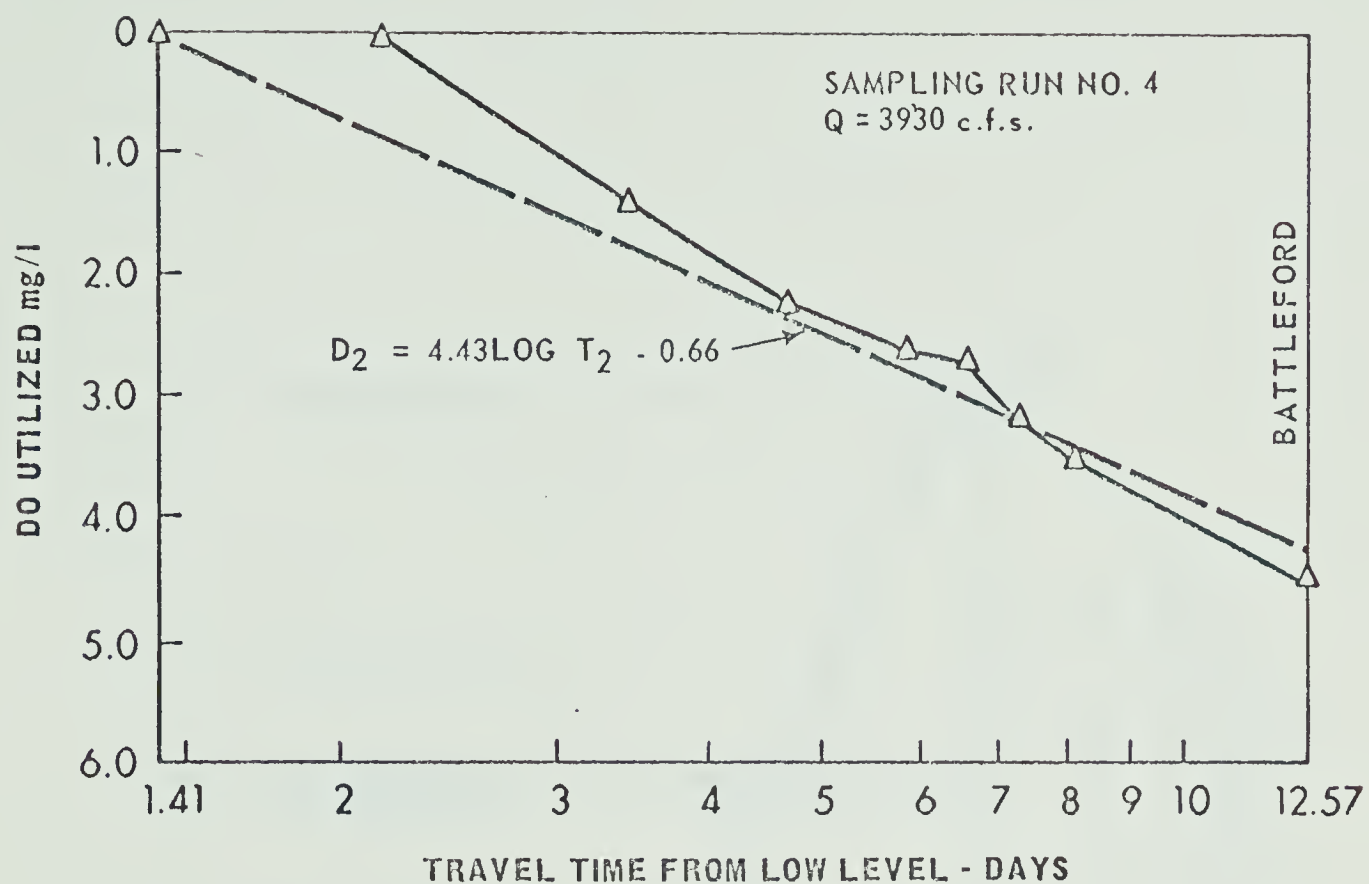


FIGURE D9: DO UTILIZATION CURVES - MARCH 1970

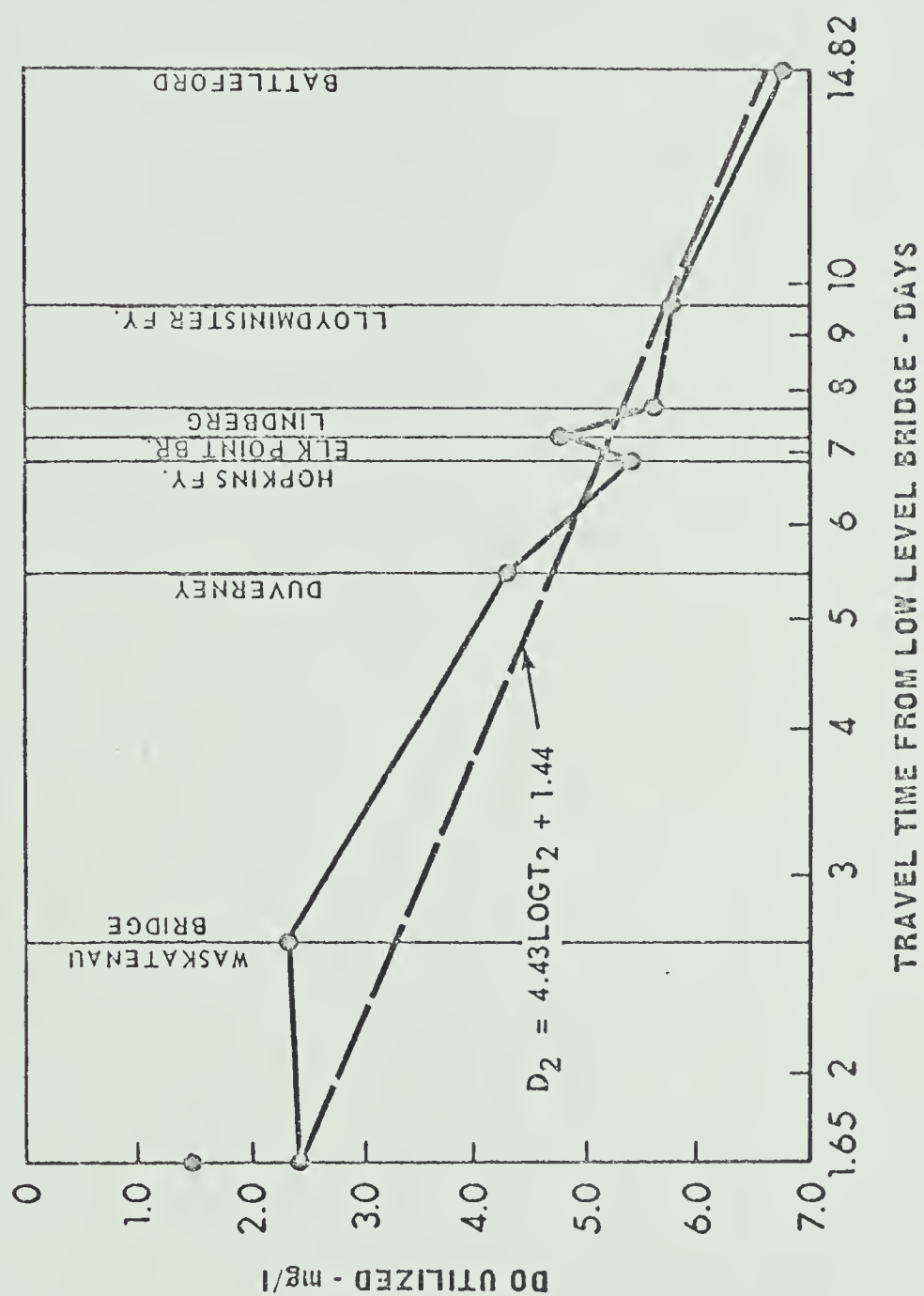


FIGURE D10: AVERAGE DO UTILIZATION IN THE NORTH
SASKATCHEWAN RIVER DURING 1966 - 67
WINTER PERIOD (from Cameron 1967)

A P P E N D I X E

APPENDIX E

LIST OF ABBREVIATIONS

BOD or BOD-5-20	Five-day, 20 degree centrigrade, biochemical oxygen demand.
°C	Degrees centigrade.
cfs	Cubic feet per second.
DC	Direct current.
DO	Dissolved oxygen.
°F	Degrees fahrenheit.
fps	Feet per second.
hrs	Hours.
lb	Pounds.
lb/day	Pounds per day.
mg/l	Milligrams per liter.
ml	Milliliters.
mu	Millimicrons.
mv	Millivolts.
MIGD	Million imperial gallons per day.
MPN	Most probable number.
No.	Number.
oz.	Ounce.
ppb	Parts per billion.
ppm	Parts per million.
Q	Discharge.

SS	Suspended solids.
STP	Sewage treatment plants.
usgpm	U.S. gallons per minute.
V	Volt.
VAC	Volts alternating current.



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